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(54) White optical pulse source and applications

(57) The present invention relates to a white pulse source that produces spectrally shaped white pulses of a constant optical output power over a wide wavelength range. The white pulse source includes a pump pulse source for generating pump pulses with a center wavelength $\lambda 0$ and a waveguided nonlinear optical medium with a length L. The waveguided nonlinear optical medium is characterized by two properties: the first property is that chromatic dispersion $D(\lambda 0, z)$ at the center wavelength of pump pulses in ps/nm/km is positive at an input end of said waveguided nonlinear optical medium, where $z = 0$, and decreases towards an output end. The second property is that said chromatic dispersion $D(\lambda, z)$ has a maximum value $D(\lambda p(z), z)$ at a peak wavelength $\lambda p(z)$ within a range of propagation distance given by $L1 \leqq z \leqq L$ where $0 \leqq L1 < L$, and that said chromatic dispersion $D(\lambda, z)$ has two zero-dispersion wavelengths, $\lambda 1(z)$ and $\lambda 2(z)$, where $D(\lambda 1(z), z) = D(\lambda 2(z), z) = 0$ ps/nm/km, within a range of propagation distance z where $D(\lambda p(z), z)$ shows a positive value.

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pump pulses having a center wavelength $\lambda 0$ and a waveguided nonlinear optical medium with a length of L, wherein the waveguided nonlinear optical medium is characterized by two properties: a first property being that chromatic dispersion $D(\lambda 0,z)$ at the wavelength of pump pulses $\lambda 0$ in ps/nm/km is positive at an input end of the waveguided nonlinear optical medium, where $z=0$. and decreases towards an output; and a second property being that there are two zero-dispersion wavelengths $\lambda 1(z)$ and $\lambda 2(z)$, where $D(\lambda 1(z), z) = D(\lambda 2(z), z) = 0$, within a range of propagation distance given by $L1 \leqq z \leqq L$, where $0 \leqq L1 < L$, that chromatic dispersion $D(\lambda, z)$ has a local maximum $D(\lambda p(z), z)$ at a peak wavelength $\lambda p(z)$ and that the local maximum $D(\lambda p(z), z)$ has positive values.

White pulses generate via a two stage process: a spectral broadening stage caused by adiabatic soliton compression; and a rectangular-shape forming stage caused by soliton changing into dispersive waves. The result is a generation of a white pulse spectrum, showing flatness over a wide range of wavelength.

Another object of the present invention is to provide a stable-output white pulse source to generate white pulses having stable output power and low noise characteristics.

The object has been achieved in a white pulse source, having a pump pulse generating section for producing pump pulses and a waveguided nonlinear optical medium for generating white pulses by being injected with the pump pulses, comprising a power stabilization section for controlling the optical power of pump pulses to be input into the waveguided nonlinear optical medium by reducing a noise component according to a relation of pump pulse power to noise coefficients generated in the course of a white pulse generation.

Accordingly, the white pulse source of the present invention has been applied to produce white pulses having low noise and stable output power.

Another object is to provide a low-noise optical pulse source to produce optical pulses having extremely low noise using the white pulse source of the present invention.

The object has been achieved in an optical pulse source, having a pump pulse generating section for producing pump pulses, a wave guided nonlinear optical medium for generating white pulses by being injected with the pump pulses, and a wavelength filter for filtering the white pulses to produce an optical pulse having a specific wavelength, the optical pulse source comprising a noise reducing section for controlling the optical power of pump pulses to be input into the waveguided nonlinear optical medium by reducing a noise component in the specific wavelength according to a relation of pump pulse power to noise coefficients generated in the course of a white pulse generation.

Accordingly, it is possible to generate low noise optical pulses that are not affected by power fluctuations contained in the pump pulse.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graph showing the first chromatic dispersion characteristic of a waveguided nonlinear optical medium with respect to wavelength for use in a equalized-output white optical pulse source.

Figures 2A~2C are graphs showing a refractive index profiles of the waveguided nonlinear optical medium.

Figure 3 is a graph showing a spectrum of pump pulses input into the waveguided nonlinear optical medium.

Figure 4 is a graph showing a spectrum of white pulses generated by the waveguided nonlinear optical medium having the first chromatic dispersion characteristics shown in Figure 1.

Figure 5 is an example of the output spectrum from a waveguided noNlinear optical medium whose chromatic dispersion has two zero-dispersion wavelengths but does not decrease with propagation distance.

Figure 6 is a graph showing how a white pulse spectrum evolves along a waveguided nonlinear optical medium having the first chromatic dispersion characteristics shown in Figure 1.

Figure 7 is a graph showing an example of the dependence of the spectral width of the white pulse on the effective medium length L0.

Figure 8 is a graph showing an example of the relation of the threshold value Lth of the effective medium length L0 for generating white pulses to the peak power of the pump pulses.

Figure 9 is a graph showing an example of the dependence of the spectral width of the white pulse on chromatic dispersion $D(\lambda 0, 0)$ at the input end of the waveguided nonlinear optical medium.

Figure 10 is an example of the dependence of spectral width of the white pulse on the pulse width of the pump pulse.

Figure 11 is an example of the dependence of the spectral width of the white pulse on the pump pulse width, in which chromatic dispersion $D(\lambda 0, 0)$ is a parameter.

Figure 12 is a graph showing a second chromatic dispersion characteristic of a waveguided nonlinear optical medium with respect to wavelength for use in a equalized-output white optical pulse source.

Figures 13A~13C are graphs showing a spectra of white pulses generated by the waveguided nonlinear optical medium having the chromatic dispersion characteristics shown in Figure 12 for different wavelength difference Λ.

Figure 14 is a graph showing a third chromatic dispersion characteristic of a waveguided nonlinear optical medium with respect to wavelength for use in a equalized-output white optical pulse source.

Figure 15 is a graph showing a spectrum of white pulses generated by the waveguided nonlinear optical medium

nonlinear optical medium will be presented under the following three sections dealing with white pulse sources of respective properties as defined below:

Section 1: equalized-output white pulse sources for generating white pulses with flatly broadened spectrum over a wide range of wavelength;
Section 2: stable-output white pulse sources for generating white pulses of highly stable output power and low-noise characteristics; and
Section 3: low-noise white pulse sources for generating low-noise optical pulses of extremely low noise from white pulses by the white pulse generation.

Section 1 Equalized-output White Pulse Sources and Evolution of White Pulses

First, some features of the white pulse sources in this section will be explained.

The white pulse sources in this section are comprised by a pump pulse source for generating pump pulses having a center wavelength $\lambda 0$, and the waveguided nonlinear optical medium (shortened to optical medium hereinbelow) having a length of L for generating white pulses by being injected with the pump pulses.

Chromatic dispersion $D(\lambda 0, z)$, in units of ps/nm/km, at the center wavelength $\lambda 0$ of the pump pulses in the optical medium at the input end ($z = 0$) is positive and decreases in the propagation direction of the pump pulses.

Further, within the propagation distance z of the pump pulses, where $L1 \leqq z \leqq L$ and $0 \leqq L1 < L$, the chromatic dispersion $D(\lambda, z)$ has a maximum value of $D(\lambda p(z), z)$ at a peak wavelength $\lambda p(z)$, and within a range of propagation distance z where $D(\lambda p(z), z)$ are positive, chromatic dispersion is zero (ps/nm/km) at two wavelengths $\lambda 1(z)$ and $\lambda 2(z)$.

Next, generation and evolution of the white pulses in the white pulse source will be explained.

A white pulse evolves through a two-stage process: a spectral broadening stage due to adiabatic soliton compression and a stage of rectangular shaping and output power flattening caused by solitons changing into dispersive waves.

A pump pulse injected into the optical meclium undergoes spectral broadening in the stage of adiabatic soliton compression within the propagation distance z where the chromatic dispersion $D(\lambda 0, z)$ of the optical medium is positive (anomalous dispersion) at the center wavelength $\lambda 0$. As the chromatic dispersion $D(\lambda 0, z)$ of the optical medium decreases with propagation distance z, and as the two zero-dispersion wavelengths, $\lambda 1(z)$ and $\lambda 2(z)$, approach the center wavelength $\lambda 0$ of the pump pulse, although the both edges of the spectrum of the pulse being compressed enter into the negative (normal dispersion) dispersion region, the pulse being compressed as a whole retains soliton characteristics during spectral broadening stage.

Further, as the chromatic dispersion $D(\lambda 0, z)$ decreases with increasing propagation distance z, soliton characteristics begin to be lost from the both edges of the spectrum towards the pump wavelength $\lambda 0$ and the pulse being compressed make transition from soliton pulse to a dispersive wave. Accordingly, the spectrum stops broadening at the breakdown points where the both edges of the spectrum begins to change to a dispersive wave. On the other hand, in the regions close to the pump wavelength $\lambda 0$ where the chromatic dispersion is still positive (anomalous dispersion), the spectrum still continues to broaden so that optical energy accumulates at the breakdown points to evolve into a rectangular spectral shape. As the two zero-dispersion wavelengths approach the pump wavelength $\lambda 0$, the both break down wavelengths also come near to the pump wavelength $\lambda 0$ to result in a flattened spectrum.

Figure 6 illustrates how a white pulse spectrum evolves with propagation distance z. The zero-dispersion wavelengths are indicated by broken lines in Figure 6, and, at the propagation distance L0, the two zero-dispersion wavelengths become coincident with the pump wavelength $\lambda 0$. In Figure 6, the spectrums of the pump pulses are indicated by (a) at the input end of the optical medium. As the two zero-dispersion wavelengths approaches the pump pulse wavelength, the spectrum progressively changes to a rectangular shape and, at the output end, a flattened spectrum is obtained as is shown in (e).

In the following, the white pulse source having the features described above will be described in more detail.

S1E1 Embodiment 1 in Section 1

The first embodiment of the white pulse source is comprised by a pump pulse source similar to the one shown in Figure 23 and a waveguided nonlinear optical medium (shortened to optical medium hereinbelow). However, the optical medium to be used in the white pulse source in the present invention is distinguished by a special characteristic of a chromatic dispersion with respect to wavelength and distance from the input end.

S1E1-1. A first characteristic of a chromatic dispersion

Figure 1 illustrates a first characteristic of a chromatic dispersion with respect to wavelength and distance in the optical medium to be used as a white pulse source. In the graph, the vertical axis and the horizontal axis represent

On the other hand, when only the requirement (2) is satisfied, that is, there are two zero-dispersion wavelengths but the chromatic dispersion does not decrease with the propagation distance, then, optical energy accumulates at the two breakdown points on both sides of the pump wavelength, but the breakdown points do not approach the pump wavelength, such that the rectangular shape of the spectrum cannot be evolved in the propagation direction. Such a case is illustrated in Figure 5, which does not achieve sufficient flatness as well.

Requirements for the Optical Medium and the Pump Pulse to Generate White Pulses

In the following, characteristics required for the optical medium for use in white pulse source and those for the input pump pulse will be discussed in terms of specific examples under five sub-sections 1a~1e, in Section 1, Embodiment 1.

S1E1-1a Chromatic dispersion D(λ 0, 0) at the input end and chromatic clispersion D(λ 0, L) at the output end of the optical medium

Chromatic dispersion D(λ 0, z) at the center wavelength λ 0 of the pump pulse is positive at the input end (z = 0) for the pump pulse and decreases with propagation clistance z along the optical medium. In this case, the spectrum of the white pulses, generated within the wavelength region in which the chromatic dispersion D(λ 0, z) is positive (normal dispersion) in the optical medium, begins to become rectangular at a propagation distance z = Lf where the chromatic dispersion D(λ0, Lf) becomes less than 1/40 of the chromatic dispersion D(λ0, 0) at the input end. It follows that:

$$D(\lambda 0, Lf) < D(\lambda 0, 0)/40.$$

As shown in the spectra (d) and (e) in Figure 6, the spectrum of a white pulse still evolves for a while even after propagation distance z ≧ L0 where chromatic dispersion is always negative (normal dispersion) for all wavelengths. Moreover, flattening effect improves when the pulse wave is propagated further in the normal dispersion region rather than outputting the pulse wave at propagation distance z = L0 where D(λp(L0), L0) = 0 ps/nm/km. Therefore, the chromatic dispersion D(λ0, L) at the output end (z = L) for optimum flattening is given by:

$$D(\lambda 0, L) \leqq - D(\lambda 0, 0)/40.$$

S1E1-1b The effective medium length L0 of the optical medium and spectral width of the white pulse

The effective medium length of the optical medium is defined as a propagation distance z = L0 where a relation D(λp(L0),L0) = 0. In case of chromatic dispersion characteristic shown in Figure 1, at the propagation distance z = L0, the zero-dispersion wavelengths become identical to the wavelength λ 0 of the pump pulse.

Figure 7 shows an typical example of the dependence of the spectral width of the white pulse on the effective medium length L0 of the optical medium. As seen in this example, there is a particular effective medium length L0 in an optical medium at which the spectral width begins to increase suddenly. This is termed the threshold value Lth of the effective medium length L0.

S1E1-1c Threshold value Lth of the elective medium length L0 and the peak power of the pump pulse

Figure 8 shows an typical example of the dependence of the threshold value Lth of the effective medium length L0 on the normalized peak power γP0 of the pump pulse where P0 is a peak power in W and a nonlinear coefficient γ is defined as (ω0 nNL)/(c0 A); ω0 = 2π c0/λ 0 is an angular frequency of the pump pulse and c0 is the speed of light in a vacuum; nNL is a nonlinear refractive index of the optical medium in m2/W; and A is a mode field area in m2 of the optical medium at the center wavelength λ0. The threshold value Lth becomes smaller as the peak power of the pump pulse increases according to the following expression:

$$\gamma P0\ Lth = 4.6$$

Therefore, by choosing the peak power P0 a the pump pulse and the effective medium length L0 so as to satisfy a relation:

corresponds to a spectral width of 25 nm.

In this case, the requirements for the optical medium to generate white pulses are expressed by:

$$L0 \geqq 473/D(\lambda 0, 0) + 374 - 1.8D(\lambda 0, 0) + 0.34\, D(\lambda 0, 0)^2$$

where L0 is in meter and D(λ0, 0) is in ps/nm/km.

Many of the optical materials used for nonlinear waveguides are susceptible to Raman effect. Figure 28 shows a contour graph for spectral widths in a typical optical material, fused silica, with respect to effective medium length L0 on the horizontal axis and chromatic dispersion D(λ0, 0) on the vertical axis. The values of peak power P0 and the FWHM of a pump pulse Δt were the same as those in Figure 27, respectively, at 0.5 W and 4 ps.

In the case shown in Figure 28, the requirements to produce white pulses are expressed as:

$$L0 \geqq 426 / D(\lambda 0, 0) + 308 - 1.7\, D(\lambda 0, 0) + 0.18\, D(\lambda 0, 0)^2$$

where L0 is in meter and D(λ 0, 0) is in ps/nm/km. Threshold value for the effective medium length L0 to generate white pulses has been reduced compared with the results in Figure 27. A general expression for normalized effective medium length Ln and normalized chromatic dispersion Dn at z = 0, with respect to the peak power P0 and the FWHM of a pump pulse Δt, is expressed as:

$$Ln \geqq a / Dn + b + c\, Dn + d\, Dn^2$$

where $a = 0.26 \times 10^{20}$, $b = 2.3$, $c = -0.16 \times 10^{-20}$ and $d = 0.21 \times 10^{-40}$.

S1E1-2 A second dispersion characteristic of chromatic dispersion

Figure 12 shows a second characteristic of chromatic dispersion in the optical medium for use in a white pulse source of the present invention.

A feature of the second dispersion characteristic is that the center wavelength λ0 and the peak wavelength λp(z) do not necessarily coincide with each other, but there is some tolerance for deviation in the wavelengths, represented by a wavelength differential Λ, according to the following expression:

$$\lambda p(L0) - \Lambda \leqq \lambda 0 \leqq \lambda p(L0) + \Lambda.$$

Figures 13A~13C show white pulse spectra corresponding to Λ = 30, 40 and 50 nm. When the difference between the center wavelength λ0 of the pump pulses and the peak wavelength λp(L0) is 30 or 40 nm, symmetry of the white pulse is somewhat degraded but the degree of flatness is reasonably acceptable. If the difference becomes 50 nm, flat spectrum cannot be obtained.

S1E1-3 A third dispersion characteristic of chromatic dispersion

In the examples presented above, the peak wavelength λp(L0) stayed at the same wavelength with decrease in the maximum dispersion D(λp(L0), z); however, it is not necessary that the peak wavelength λp(L0) remains unchanged with respect to the propagation distance z. For example, as shown in Figure 14, the optical medium may allow some shift in the peak wavelength λp(L0) as the maximum dispersion D(λp(L0), z) decreases. This third dispersion characteristic is produced in practice when only the diameters of the core and the cladding(s) in the longitudinal direction are altered. The white pulse spectrum generated from a white pulse source having an optical medium of such dispersion characteristics is shown in Figure 15. It can be seen that the white pulses having high degree of flatness over a wide range of wavelengths are obtained, as in the case of a medium having the first or second characteristic of chromatic dispersion.

Figure 29 shows another example of white pulse spectrum experimentally generated from an optical medium designed and manufactured according to the third dispersion characteristic. The optical meclium was a single-mode optical fiber which generated white pulses having a equalized spectrum over a spectral range in excess of 200 nm.

S1E7 Other Configurations for white pulse source

In each of the foregoing embodiments, it is possible to stabilize the polarization of the output white pulses by providing the waveguided nonlinear optical medium with polarization-maintaining property.

Also, in each of the foregoing embodiments, it is permissible to provide an optical amplifier to amplify pump pulses before the input end of the optical medium 2. This will enable to generate white pulses even by using a pump pulse source with low power output.

The peak observed in the white pulse spectrum at the center wavelength $\lambda 0$ of the pump pulse corresponds to the pedestal of the pump pulse which did not convert to white pulses.

In each of the foregoing embodiments, it is permissible to provide a wavelength filter to eliminate or suppress the peak at the pump pulse wavelength at the output end of the optical medium. This enables to eliminate or suppress the peak whose optical power density is higher than that of the white pulse.

Summarizing the fundamentals of the foregoing embodiments, the present white pulse source is characterized by: 1) having an optical medium in which the chromatic dispersion of pump pulses at the center wavelength $\lambda 0$ diminishes from a positive value to a vicinity of zero ps/nm/km in the direction of propagation of the pump pulse; and 2) the chromatic dispersion characteristic has a maximum value when chromatic dispersion at wavelength $\lambda 0$ is in the vicinity of zero ps/nm/km, and has two zero-dispersion wavelengths when the maximum value is positive. This structure prompts the spectrum of the input pump pulses to be broadened through soliton compression and to become rectangular and flat through a process in which a soliton pulse changes into a dispersive wave.

By utilizing an optical medium with optical gain for the waveguided nonlinear optical medium, white pulses can be produced under less restrictive conditions of lower power of pump pulse or shorter length of optical medium.

Section 2: Stable-output White Pulse Sources

First, important features of the white pulse sources described in this section will be explained.

The white pulse sources in this sections produce white pulses with low noise by controlling the pump pulse power to reduce the noise coefficient in the course of the white pulse generation, according to a relation of noise coefficient to the pump pulse power.

The relation between the noise coefficient in white pulse generation and the pump pulse power into the optical medium will be explained. The noise coefficient is defined as a ratio of power fluctuation components included in the white pulses (wavelength components) generated from the optical medium to power fluctuation components included in the pump pulse.

Figure 32 is a schematic configuration for determining the noise coefficient in white pulse generation. The pump pulse source 1 generates pump pulses at a repetition frequency f0. This pump pulse is superimposed with a power fluctuation component (frequency Δf, modulation index M_{in}) in an optical power modulator 4, and is input into the optical medium 2 at a given optical power through an optical attenuator 5. When the white pulse output from the optical medium 2 is filtered through a wavelength filter 3, the filtered white pulse contains a fluctuation component (modulation index M_{out}). A noise coefficient for each wavelength component in a white pulse is obtained as a ratio, M_{out}/M_{in}, of the output modulation index M_{out} to the input modulation index M_{in}.

In Figure 32, it is shown that the modulation index M_{in} is defined as a ratio b/a, where b is the fluctuation component at frequencies $f0 \pm \Delta f$ and a is the carrier component at repetition frequency f0, and M_{out} is defined as a ratio d/c, where d is the fluctuation component at frequencies $f0 \pm \Delta f$ and c is the carrier component at repetition frequency f0.

Figure 33 is an example of the measurement results of noise coefficient in the white pulses to peak power of pump pulse obtained by the arrangement in Figure 32. The values shown in Figure 33 are actual measurements of the noise coefficients obtained by filtering the white pulses at different wavelengths. The center wavelength of the pump pulse is 1535 nm.

The relation of the noise coefficient to the pump pulse power is dependent on the pulse width of the pump pulse and the chromatic dispersion characteristics in the optical medium, but commonly, the plots of the noise coefficient to the pump pulse power show the following features.

As indicated in Figure 33, the noise coefficient shows local minima with respect to pump pulse power, and the pump pulse powers where the noise coefficient has local minima shift upwards as the wavelength of the filtered white pulse shifts further from the pump wavelength. For example, at a wavelength 1505.03 nm (indicated by circles), the noise coefficient has local minima at around 2.25 and 2.45 W, but for a wavelength 1476.92 nm (squares), it has the corresponding local minima at around 2.35 and 2.51 W. It was also observed that the higher the pump pulse power, the smaller the noise coefficient as a whole for each wavelength component.

When the noise coefficient is higher than 0 dB, power fluctuations in the pump pulse are amplified and transferred to the wavelength components in the white pulse, therefore, the waveform of the white pulse becomes distorted and the signal/noise ratio is degraded. If the noise coefficient is less than 0 dB, power fluctuation in the pump pulse are

and the noise coefficient is measured in real-time, so that the pump pulse power can be feedback-controlled according to the measured noise coefficient.

Figure 35 shows Embodiment 3 in Section 2.

In this embodiment, the pump pulse generation section 51 shown in Figure 30 is comprised by: a pump pulse source 1 which is capable of adjusting the output power and an optical power modulator 4; and the stabilization section 50 shown in Figure 30 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses generated in the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in} into the optical medium 2 which generates white pulses. The modulation index M_{out} contained in the output white pulses is measured by the modulation component measuring section 10 through an optical branching section 6 after the output end of the optical medium 2. Optical power control section 11 figures out a noise coefficient as a ratio M_{out}/M_{in}, and controls the pump pulse source 1 to minimize the noise coefficient related to pump pulse power.

Figure 36 shows Embodiment 4 in Section 2.

In this embodiment, the pump pulse generation section 51 shown in Figure 30 is comprised by: a pump pulse source 1, an in-line optical power adjusting section 9, and an optical power modulator 4; and the stabilization section 50 shown in Figure 30 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses output from the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in} and are then input through an optical power adjusting section 9, into the optical medium 2 which generates white pulses. The modulation index M_{out} contained in the output white pulses is measured by monitoring the optical power of the white pulse in the modulation component measuring section 10 through an optical branching section 6 after the output end of the optical medium 2. Optical power control section 11 figures out a noise coefficient as a ratio M_{out}/M_{in}, and controls the optical power adjusting section 9 to minimize the noise coefficient related to pump pulse power. Also, the optical power control section 9 may use either or both of optical amplifier device or optical attenuator device.

In Figure 36, the optical power adjusting section 9 is located before the optical power modulation device 4, but it is permissible to locate the optical power modulation device 4 after the optical power adjusting section.

In Embodiments 5 and 6, the modulation index M_{in} to be superimposed on the pump pulse at the input side of the optical medium 2 is made constant. In this case, the pump pulse power is adjusted according to the modulation index M_{out} because the noise coefficient corresponds to the modulation index M_{out} contained in the white pulses.

Figure 37 shows Embodiment 5 in Section 2.

In this embodiment, the pump pulse generation section 51 shown in Figure 30 is comprised by: a pump pulse source 1 which is capable of adjusting the output power and an optical power modulator 4; and the stabilization section 50 shown in Figure 30 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses generated in the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in}, and into the optical medium 2 which generates white pulses. The modulation index M_{out} contained in the output white pulses is measured by monitoring the optical power of the white pulse in the modulation component measuring section 10 through an optical branching section 6 after the output end of the optical medium 2. Optical power control section 11 controls the pump pulse source 1 to minimize the modulation index M_{out} of the white pulses being measured by the modulation component measuring section 10, and adjusts the pump pulse power to be input into the optical medium 2.

Figure 38 shows Embodiment 6 in Section 2.

In this embodiment, the pump pulse generation section 51 shown in Figure 30 is comprised by: a pump pulse source 1, an in-line optical power adjusting section 9, and an optical power modulator 4; and the stabilization section 50 shown in Figure 30 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses generated in the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in} and are then input through the optical power adjusting section 9, into the optical medium 2 which generates white pulses. The modulation index M_{out} contained in the output white pulses is measured by moninoring the optical power of the white pulse in the modulation component measuring section 10 through an optical branching section 6 after the output end of the optical medium 2. Optical power control section 11 controls the optical power adjusting section 9 to minimize the modulation index M_{out} of the white pulses being measured by the modulation component measuring section 10, and adjusts the pump pulse power to be input into the optical medium 2. Also, the optical power control section 9 may use either or both of optical amplifying device or optical attenuating device.

In Figure 38, the optical power adjusting section 9 is located before the optical power modulation device 4, but it

noise in the white pulses, by disposing a wavelength filter 3 between the optical branching section 6 after the output end of the optical medium 2 and the noise component measuring section 12.

S2E11 Embodiment 11

In each of the foregoing embodiments 2, 4, 6, 8 and 10 in Section 2, it is also permissible to input with external pump pulses for generating white pulses.

Figure 45 shows Embodiment 11 in Section 2 which accepts external pump pulses through a pump pulse input section 55 into the optical medium 2, and a stabilization section 50 is provided to stabilize the optical power of white pulses output from the optical medium 2.

As is mentioned in those corresponding embodiments 2, 4, 6, 8 and 10, the stabilization section 50 is provided with a function to control the pump pulse input section 55 to adjust optical power of pump pulse to be input into the optical medium 2 to reduce the noise component in the output white pulses according to the relation of the noise coefficient of the white pulses generated in the optical medium 2 to optical power of the pump pulses.

Section 2a Noise Components Measuring Method

Figure 43 shows an example of measuring the noise components output from a white pulse source utilizing a harmonically mode-locked pulse laser as a pump pulse source.

This method is valid when using a harmonically mode-locked pulse laser generating repetition frequency components Nf (where f is fundamental mode frequency and Nis an integer larger than 2) as the pump pulse source 1. Frequency components other than the repetition frequency components or their harmonic components nNf(n is an integer) contribute as intensity noise to the output pump pulses, therefore, these frequency components Mf(M is an integer other than nN) are monitored and the pump pulse power is adjusted to minimize components at frequencies Mf in the white pulses.

Figure 44 shows an example of measuring the low-frequency noise components output from a white pulse source.

This method is valid when using a mode-locked pulse laser as the pump pulse source 1. Spectral components at a relaxation oscillation frequency from such laser source contribute as low-frequency intensity noise, which can be monitored and used as a feedback flag to reduce its value.

Section 2b Other Embodiments

In each of the foregoing embodiments, by using a white pulse source which generates a equalized spectrum over a wide bandwidth, the wavelength-dependency of the spectrum of the output white pulses can be reduced considerably. Such a white pulse source, as explained in Section 1, can be realized by using a waveguided nonlinear optical medium 2 that exhibits a chromatic dispersion characteristics shown in Figures 1, 13 and 15.

In other words, the optical medium 2 should satisfy the requirements that: (1) the chromatic dispersion at the wavelength of the pump pulse decreases from positive value to less than zero in the propagation direction of the pump pulse; and (2) over the entire or partial range of propagation distance in the optical medium, the chromatic dispersion characteristic shows two zero-dispersion wavelengths, both of which approach the wavelength of the pump pulse with the propagation distance from the input end.

It will be recalled that Figure 1 is an example of the chromatic dispersion characteristic where the center wavelength $\lambda 0$ of pump pulses coincides with the peak wavelength of the chromatic dispersion, and Figure 12 is an example of the chromatic dispersion characteristic where the center wavelength $\lambda 0$ of pump pulses does not necessarily coincide with the peak wavelength of the chromatic dispersion, and Figure 14 is an example in which the peak wavelength of the chromatic dispersion varies along the propagation direction.

By using a waveguided nonlinear optical medium designed according to the present embodiment, a stable-output white pulse source will be able to generate white pulses having a equalized-output optical power over a wide bandwidth.

Also, in each of the foregoing embodiments, it is possible to stabilize the polarization of the output white pulses by providing the waveguided nonlinear optical medium with polarization-maintaining property for generating stable-output white pulses.

Also, in each of the foregoing embodiments, it is permissible to provide an optical amplifier to amplify pump pulses before the input end of the optical medium 2. This will enable to generate white pulses even by using a pump pulse source with low power output.

In each of the foregoing embodiments, it is also permissible to provide a wavelength filter to eliminate or suppress the spectral peak at the pump pulse wavelength which corresponds to the pedestal of the pump pulse as described in Section 1. This enables to eliminate or suppress the spectral peak whose optical power density is higher than that of the white pulse.

S3E1 Embodiment 2 in Section 3

In Embodiment 1, pump pulse generation section 61 was comprised by a pump pulse source whose output power is adjustable, but in Embodiment 2, pump pulse generation section 61 is comprised by a pump pulse source and an in-line optical power adjusting section which controls the pump pulse power to be input into the optical medium 2.

Figure 49 is a schematic configuration of the low-noise optical pulse source of Embodiment 2 in Section 3. Figure 49A shows a feed-back scheme and Figure 49B shows a feed-forward scheme. The stabilization section 60 is comprised by an optical power measuring section 7 and an optical power control section 8.

Pump pulses generated in the pump pulse source 1 are input, through the optical power adjusting section 9, into the optical medium 2, and the output white pulses are filtered by a wavelength filter 3 to output optical pulses of a specific wavelength. The optical power of pump pulses is monitored by the optical power measuring section 7 through the optical branching section 6 disposed on the fore- or aft-stage of the optical power adjusting section 9. The optical power control section 8 controls the optical power adjusting section 9 to minimize the difference between the optical power of pump pulses monitored by the power measuring section 7 and a target value to adjust the pump pulse power into the optical medium 2 at the target value. The optical power control section 9 may be represented by either or both of optical amplifier and optical attenuator.

S3E3~S3E6 Embodiments 3 to 6 in Section 3

Embodiments 1 and 2 were based on an approach of pre-determining a relation of the noise coefficient to pump pulse power, and the pump pulse power was controlled so that the noise coefficient at the wavelength specified by a wavelength filter 3 is minimized to less than 0 dB. In contrast, in the following Embodiments 3~6, fluctuation components are deliberately superimposed on the pump pulses and the noise coefficient depending on pump pulse power is measured in real-time, so that the pump pulse power can be feedback-controlled according to the measured noise coefficient.

Figure 50 shows Embodiment 3 in Section 3.

In this embodiment, the pump pulse generation section 61 shown in Figure 46 is comprised by: a pump pulse source 1 which is capable of adjusting the output power and an optical power modulator 4; and the noise reduction section 60 shown in Figure 46 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses generated in the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in} into the optical medium 2 which generates white pulses which are filtered through a wavelength filter 3 to produce optical pulses of a specific wavelength. The modulation index M_{out} contained in the output pulses from the wavelength filter 3 is measured by the modulation component measuring section 10 through an optical branching section 6 disposed after the output end of the wavelength filter 3. Optical power control section 11 figures out a noise coefficient as a ratio M_{out}/M_{in}, and controls the pump pulse source 1 so as to minimize the noise coefficient related to pump pulse power.

Figure 51 shows Embodiment 4 in Section 3.

In this embodiment, the pump pulse generation section 61 shown in Figure 46 is comprised by: a pump pulse source 1, an in-line optical power adjusting section 9, and an optical power modulator 4; and the noise reduction section 60 shown in Figure 46 is comprised by an optical power control section 11 and a modulation component measuring section 10.

Pump pulses generated in the pump pulse source 1 are input through the optical power modulator 4 to superimpose a power fluctuation of a given level of modulation index M_{in} and are then input through an optical power adjusting section 9, into the optical medium 2 which generates white pulses which are filtered through a wavelength filter 3 to produce optical pulses of a specific wavelength. The modulation index M_{out} contained in the output pulses from the wavelength filter 3 is measured by the modulation component measuring section 10 through an optical branching section 6 disposed after the output end of the wavelength filter 3. Optical power control section 11 figures out a noise coefficient as a ratio M_{out}/M_{in}, and controls the optical power adjusting section 9 so as to minimize the noise coefficient related to pump pulse power. Also, the optical power control section 9 may use either or both of optical amplifying device or optical attenuating device.

In Figure 51, the optical power adjusting section is provided after the optical power modulation device 4, but it may be provided before the device 4.

Embodiments 5 and 6 controlled the pump pulse power according to M_{out} contained in the white pulses, because for a constant value of the modulation index Min superimposed on the pump pulse, the noise coefficient is equivalent to modulation index M_{out}.

Figure 52 shows Embodiment 5 in Section 3.

In this embodiment, the pump pulse generation section 61 shown in Figure 46 is comprised by: a pump pulse

S3E9 Embodiment 9

In each of the foregoing embodiments 2, 4, 6 and 8 in Section 3, it is also permissible to input with external pump pulses for generating white pulses.

Figure 56 shows Embodiment 9 in Section 3 which accepts external pump pulses through a pump pulse input section 65 into the optical medium 2, and a noise reduction section 60 is provided to minimize the noise level in the optical pulses output from the wavelength filter 3.

As is mentioned in those corresponding embodiments 2, 4, 6 and 8, the noise reduction section 60 is provided with a function to control the pump pulse input section 65 to adjust optical power of pump pulse to be input into the optical medium 2 to reduce the noise level in the optical pulses output from the wavelength filter 3 even lower than that of the pump pulses according to the relation of the noise coefficient to pump pulse power.

S3a Noise Components Measuring Method

The method of measuring the noise components is the same as that explained in Section 2 with reference to Figures 44 and 45, and it will not be repeated.

Section 3b Other Embodiments

The effects of the low-noise white pulse source described in Section 3 are very much the same as those in Section 2 and will not be repeated.

It is important to emphasize, however, that the optical medium 2 should again satisfy the same requirements as expressed previously, namely that: (1) the chromatic dispersion at the wavelength of the pump pulse decreases from positive value to less than zero in the propagation direction of the pump pulse; and (2) over the entire or partial range of propagation distance in the optical medium, the chromatic dispersion characteristic shows two zero-dispersion wavelengths, both of which approach the wavelength of the pump pulse with the propagation distance from the input end.

By using the present design of the waveguided nonlinear optical medium as explained in this section, it is possible to reduce the wavelength-dependency of the filtered optical pulse from the white pulse generated because of its equalized spectrum over a wide bandwidth.

In each of the foregoing embodiments, the filter 3 may be a single wavelength, a multiple wavelengths or a variable wavelength filter. When using a multiple-wavelength filter, the modulation component or noise component to be monitored are the maximums in each wavelength band.

As in Section 2, the waveguided nonlinear optical medium 2 in each of the foregoing embodiments may be provided with polarization-maintaining property to generate polarization-maintaining white pulses so that optical waves having a stable polarization may be propagated in the optical medium. It follows that any filtered optical pulse would also have a stable optical polarization.

As in Section 2, in each of the foregoing embodiments, it is permissible to provide an optical amplifier to amplify pump pulses before the input end of the optical medium 2. This will enable to generate white pulses even by using a pump pulse source with low power output.

Summarizing the above, the present low-noise pulse source minimizes the noise coefficient of the filtered optical pulse from the white pulses to less than 0 dB by controlling the optical power of pump pulses input into the optical medium, thereby generating optical pulses which have lower noise than that of the pump pulses.

Claims

1. A white pulse source comprised by a pump pulse source for generating pump pulses having a center wavelength $\lambda 0$ and a waveguided nonlinear optical medium having a length of an L meter, wherein said waveguided nonlinear optical medium is characterized by two properties: a first property being that chromatic dispersion $D(\lambda 0,z)$ at the center wavelength of pump pulses in ps/nm/km is positive at an input end of said waveguided nonlinear optical medium, where $z=0$, and decreases towards an output end; and a second property being that said chromatic dispersion $D(\lambda, z)$ has a maximum value $D(\lambda p(z), z)$ at a peak wavelength $\lambda p(z)$ within a range of propagation distance given by $L1 \leqq z \leqq L$ where $0 \leqq L1 < L$, and that said chromatic dispersion $D(\lambda,z)$ has two zero-dispersion wavelengths, $\lambda 1(z)$ and $\lambda 2(z)$, where $D(\lambda 1(z), z) = D(\lambda 2(z), z) = 0$ ps/nm/km, within a range of propagation distance z where $D(\lambda p(z), z)$ shows a positive value.

2. A white pulse source according to claim 1, wherein said two zero-dispersion wavelengths, $\lambda 1(z)$ and $\lambda 2(z)$ move closer to each other as said maximum value $D(\lambda p(z), z)$ of chromatic dispersion decreases towards zero ps/nm/km.

chromatic dispersion Dn at z = 0 in said waveguided nonlinear optical medium are related by:

$$Ln \geqq a/Dn + b + c\,Dn + d\,Dn^2$$

where $a = 0.30 \times 10^{20}$, $b = 2.9$, $c = -0.17 \times 10^{-20}$ and $d = 0.40 \times 10^{-40}$ and said normalized effective medium length Ln is given by $Ln = \gamma\, P0\, L0$, and the normalized chromatic dispersion at z = 0 is given by $Dn = D(\lambda 0, 0)/(\gamma\, P0\, \Delta t^2)$; P0 in W is a peak power of said pump pulse; Δt in second is a full-width half-maximum of said pump pulse; L0 is a effective medium length of said waveguided nonlinear optical medium where $D(\lambda p(L0), L0)$ is zero in ps/nm/km.

12. A white pulse source according to claim 1, wherein said waveguided nonlinear optical medium is comprised by either a double clad, a triple clad or a quadruple clad configuration, and diameters or a refractive indices of a core or claddings are varied along said waveguided nonlinear optical medium to change chromatic dispersion characteristics in said waveguided nonlinear optical medium.

13. A white pulse source according to claim 12, wherein said waveguided nonlinear optical medium has a double cladding configuration wherein average refractive indices in a core, a first cladding and a second cladding denoted by n0, n1 and n2, respectively, are related such that n0 > n2 > n1.

14. A white pulse source according to claim 12, wherein said waveguided nonlinear optical medium has a triple cladding configuration wherein average refractive indices in a core, a first cladding, a second cladding and third cladding denoted by n0, n1, n2 and n3, respectively, are related such that n0 > n2 > n3 >n1.

15. A white pulse source according to claim 12, wherein said waveguided nonlinear optical medium has a triple cladding configuration wherein average refractive indices in a core, a first cladding, a second cladding, a third cladding and a fourth cladding denoted by n0, n1, n2, n3 and n4, respectively, are related such that:

$$n0 > n2 > n4 > n3 > n1 \text{ or } n0 > n2 > n4 > n3 = n1.$$

16. A white pulse source according to claim 1, wherein said waveguided nonlinear optical medium is a polarization-maintaining waveguided nonlinear optical medium.

17. A white pulse source according to claim 1, wherein said waveguided nonlinear optical medium is provided with an optical amplifying device.

18. A white pulse source accorcling to claim 1, wherein a wavelength filter is provided at an output end of said waveguided nonlinear optical medium to eliminate or suppress a spectral peak of white pulses output from said waveguided nonlinear optical medium at a center wavelength of said pump pulse.

19. A white pulse source according to claim 1, wherein said waveguided nonlinear optical medium is a waveguided nonlinear optical medium with gain for amplifying pump pulses.

20. A white pulse source according to claim 1, wherein waveguided nonlinear optical medium is a rare-earth-element doped nonlinear optical medium; a pump light source is provided for causing population inversion in said rare-earth-element doped nonlinear optical medium; and a pump light input section is provided for inputting pump light into said rare-earth-element doped nonlinear optical medium.

21. A white pulse source according to claim 1, wherein said waveguided nonlinear optical medium is susceptible to Raman effect.

22. A white pulse source according to claim 21, wherein a normalized effective medium length Ln and normalized chromatic dispersion Dn at z = 0 in said waveguided nonlinear optical medium are related by:

$$Ln \geqq a/Dn + b + c\,Dn + d\,Dn^2$$

where $a = 0.26 \times 10^{20}$, $b = 2.3$, $c = -0.16 \times 10^{-20}$ and $d = 0.21 \times 10^{-40}$ and said normalized effective medium length

wavelength band contained in optical input into said modulation component measuring section.

33. A white pulse source according to claim 30, wherein said power stabilization section includes a wavelength filter disposed in front of said modulation component measuring section for filtering optical component in a specific wavelength band contained in optical input into said modulation component measuring section.

34. A white pulse source according to claim 31, wherein said power stabilization section includes a wavelength filter disposed in front of said modulation component measuring section for filtering optical component in a specific wavelength band contained in optical input into said modulation component measuring section.

35. A white pulse source according to claim 27, wherein a noise coefficient related to a white pulse generating process is given by a ratio of an power fluctuation component contained in white pulses output from said waveguided nonlinear optical medium, to an power fluctuation component contained in pump pulses to be input into said waveguided nonlinear optical medium.

36. A white pulse source according to claim 31, wherein said pump pulse source is comprised by a harmonically mode-locked pulse laser having a repetition frequency component *Nf* where *f* is a fundamental mode frequency and *N* is an integer not less than 2; and said noise component measuring section monitors said frequency components at *Mf* where *M* is an integer different from a multiple integer of *N*.

37. A white pulse source according to claim 31, wherein said noise component measuring section monitors low frequency noise components contained in pump pulses.

38. A white pulse source according to claim 37, wherein said pump pulse source is comprised by a mode-locked pulse laser and said noise component measuring section monitors a relaxation oscillation component contained in optical output of a mode-locked pulse laser as a noise component.

39. A white pulse source according to claim 27, wherein said pump pulse generation section includes a pump pulse source whose optical output power is adjustable.

40. A white pulse source according to claim 27, wherein said pump pulse generation section includes an optical power adjusting section for adjusting an output power of pump pulses output from said pump pulse generation section.

41. A white pulse source according to claim 27, wherein said waveguided nonlinear optical medium is comprised by a waveguided nonlinear optical medium claimed in claim 1.

42. A white pulse source according to claim 27, wherein said waveguided nonlinear optical medium is a polarization-maintaining waveguided optical medium.

43. A white pulse source according to claim 27 provided with an optical amplifying device to amplify pump pulses to be input into said waveguided nonlinear optical medium.

44. A white pulse source according to claim 27 provided with a wavelength filter to eliminate or suppress a spectral peak of white pulses output from said waveguided nonlinear optical medium at a center wavelength of said pump pulse.

45. An optical pulse source, having a pump pulse generation section for generating pump pulses and a waveguided nonlinear optical medium for generating white pulses by being injected with said pump pulses, and a wavelength filter for filtering said white pulses to produce optical pulses having specific wavelength component(s), comprising a noise reduction section which controls optical power of pump pulses to be input into said waveguided nonlinear optical medium for reducing a noise component in said specific wavelength component(s) according to a dependence of noise coefficients related to a white pulse generating process on optical power of pump pulses.

46. An optical pulse source according to claim 45, wherein said noise reduction section controls optical power of pump pulses to be input into said waveguided nonlinear optical medium for minimizing a noise coefficient to not more than 0 dB, according to a pre-determined dependence of noise coefficients related to a white pulse generating process on optical power of pump pulses.

58. A white pulse source according to claim 45, wherein said waveguided nonlinear optical medium is a polarization-maintaining waveguided optical medium.

59. A white pulse source according to claim 45 provided with an optical amplifying device to amplify pump pulses to be input into said waveguided nonlinear optical medium.

60. A white pulse source according to claim 27, wherein said pump pulse generation section is comprised by:
an pump pulse input section for accepting external pump pulses.

61. A white pulse source according to claim 45, wherein said pump pulse generation section is comprised by:
an pump pulse input section for accepting external pump pulses.

FIG.2A

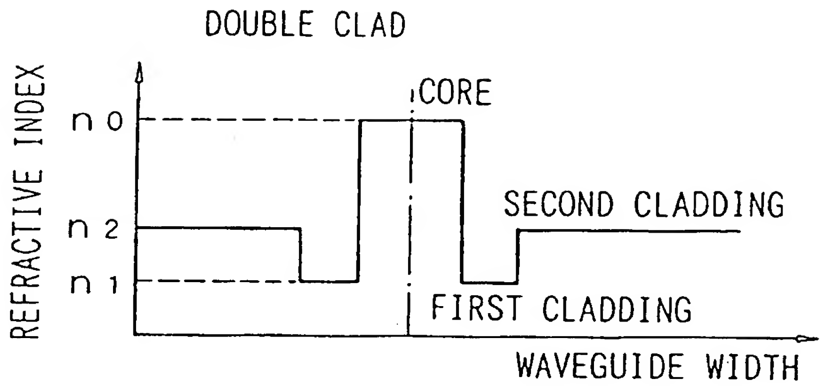


FIG.2B

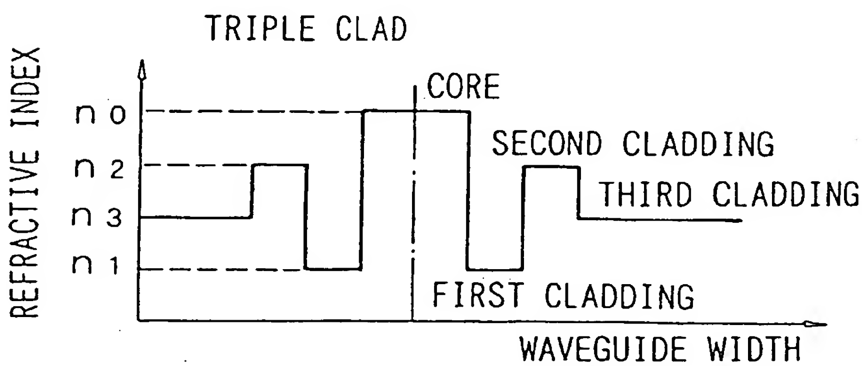


FIG.2C

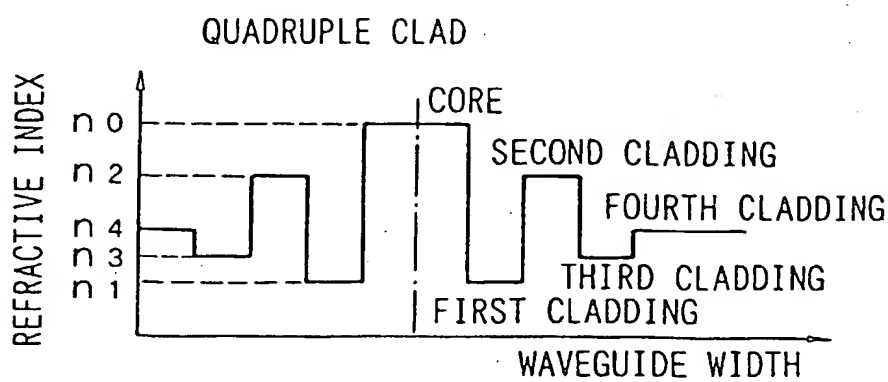


FIG.5

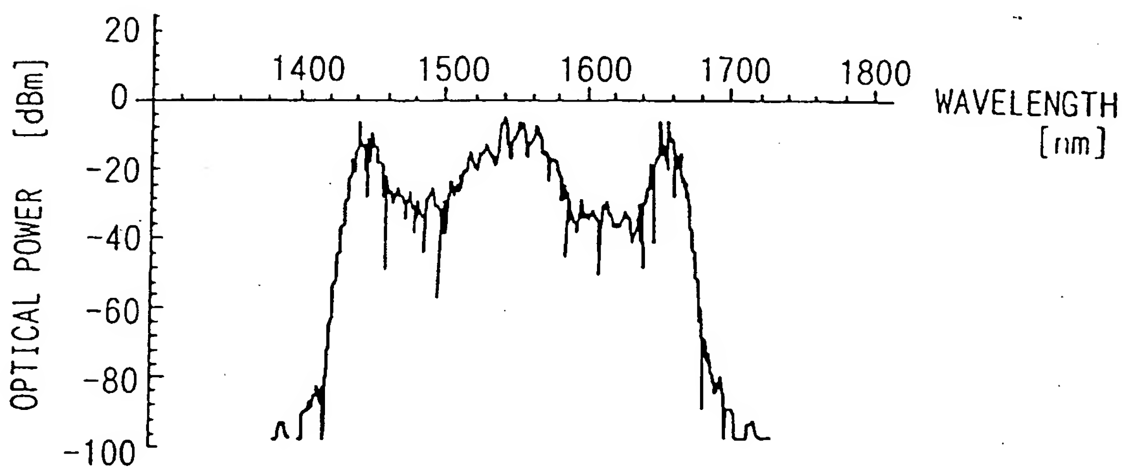

20
0
-20
-40
-60
-80
-100
OPTICAL POWER [dBm]
1400
1500
1600
1700
1800
WAVELENGTH
[nm]

FIG.7

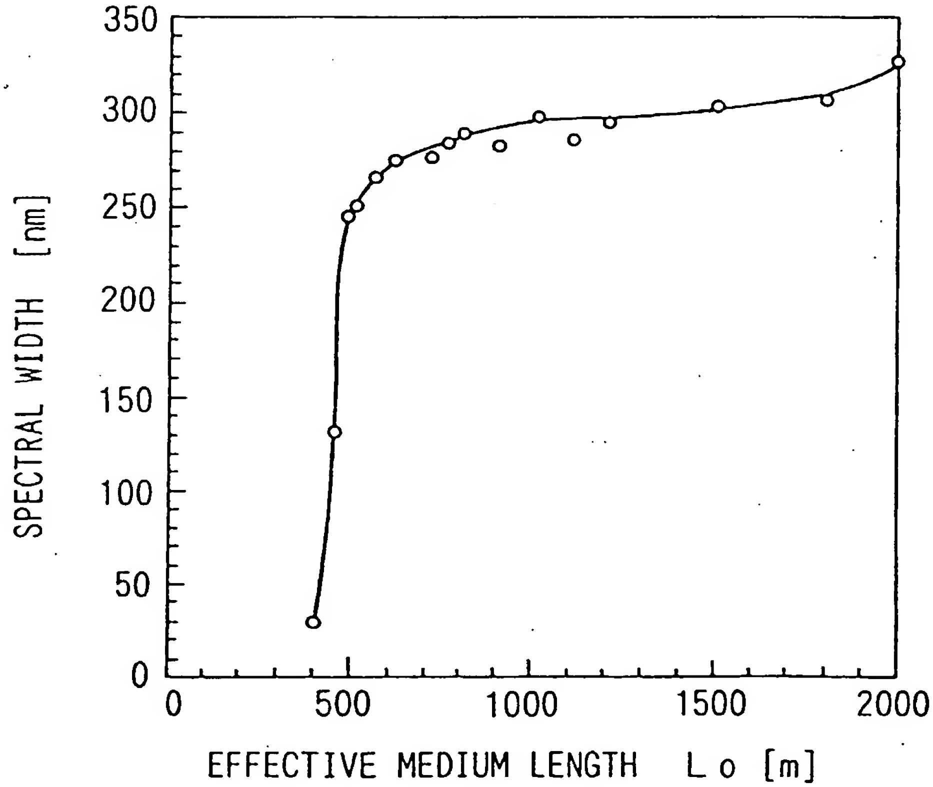
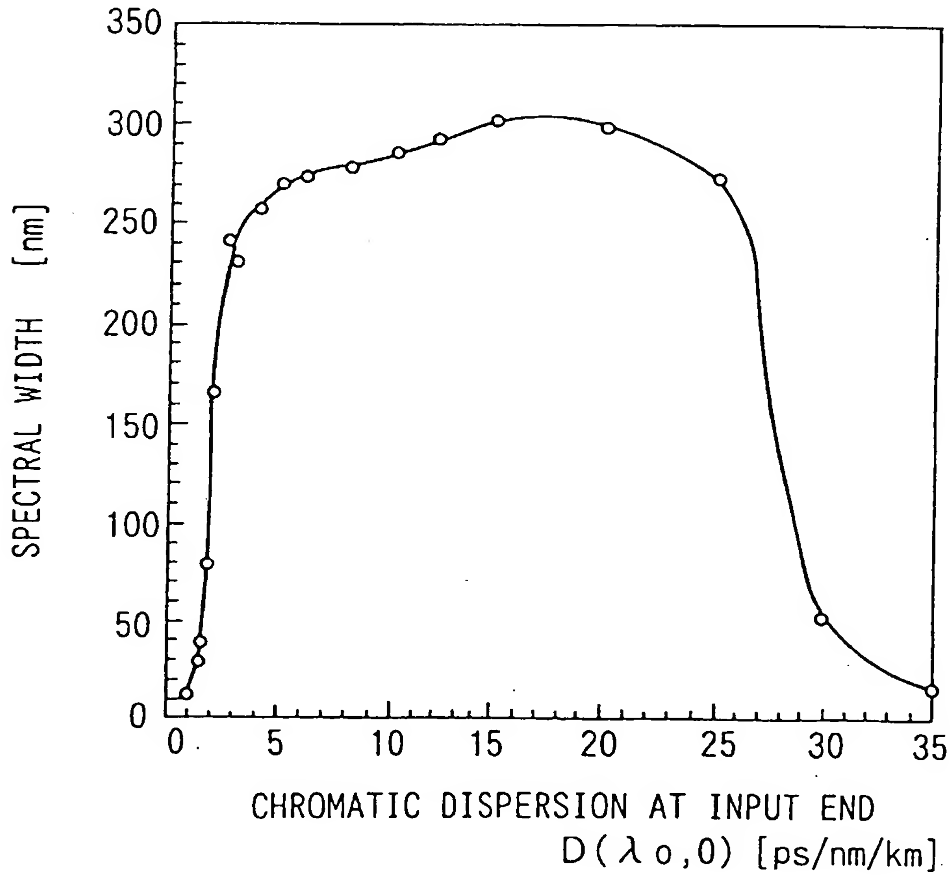

SPECTRAL WIDTH [nm]
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
EFFECTIVE MEDIUM LENGTH Lo [m]

FIG.9



SPECTRAL WIDTH [nm]
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
CHROMATIC DISPERSION AT INPUT END
D(λ o,0) [ps/nm/km]

FIG.11

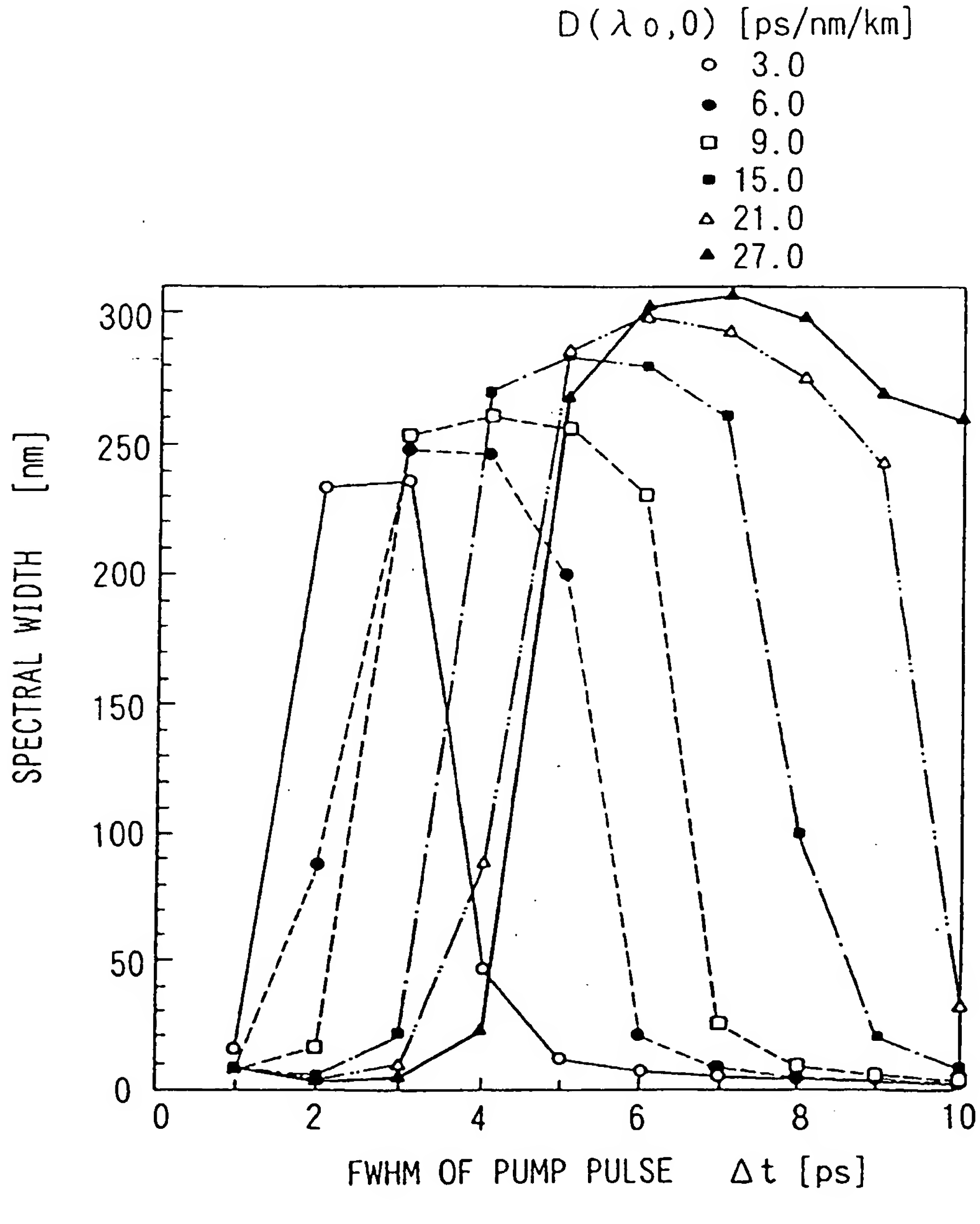

D(λo,0) [ps/nm/km]
3.0
6.0
9.0
15.0
21.0
27.0
300
250
200
150
100
50
0
SPECTRAL WIDTH [nm]
0
2
4
6
8
10
FWHM OF PUMP PULSE Δt [ps]

FIG.13A

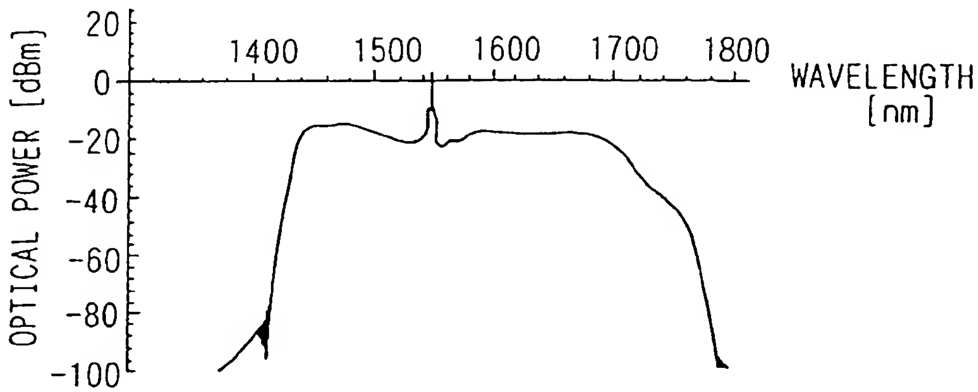


FIG.13B

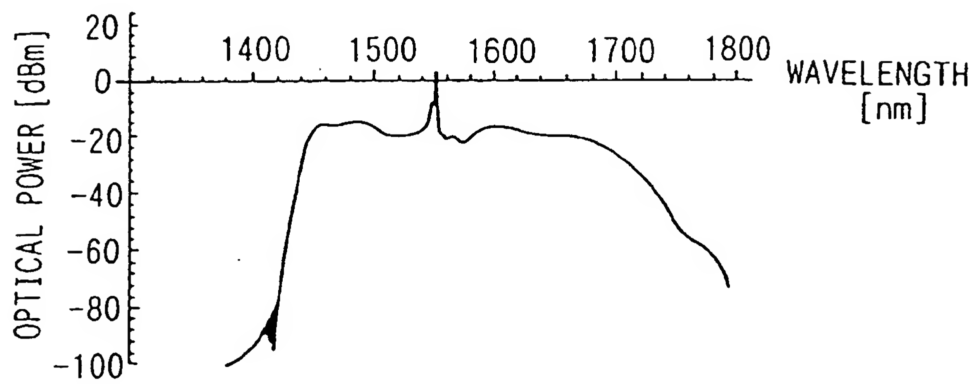


FIG.13C

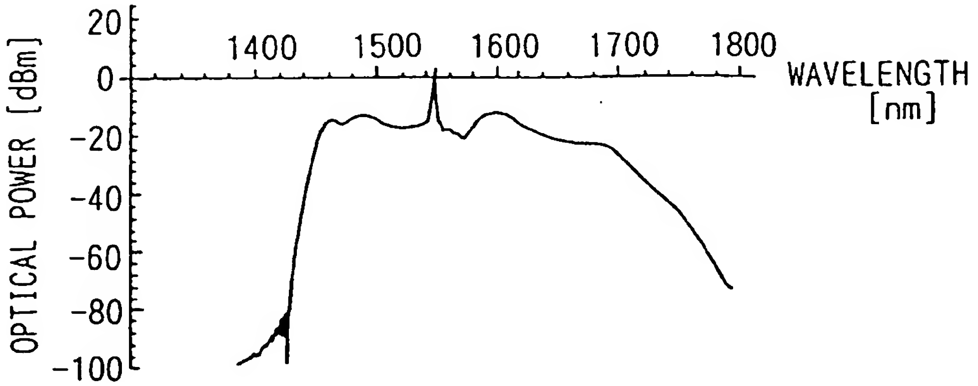


FIG.16

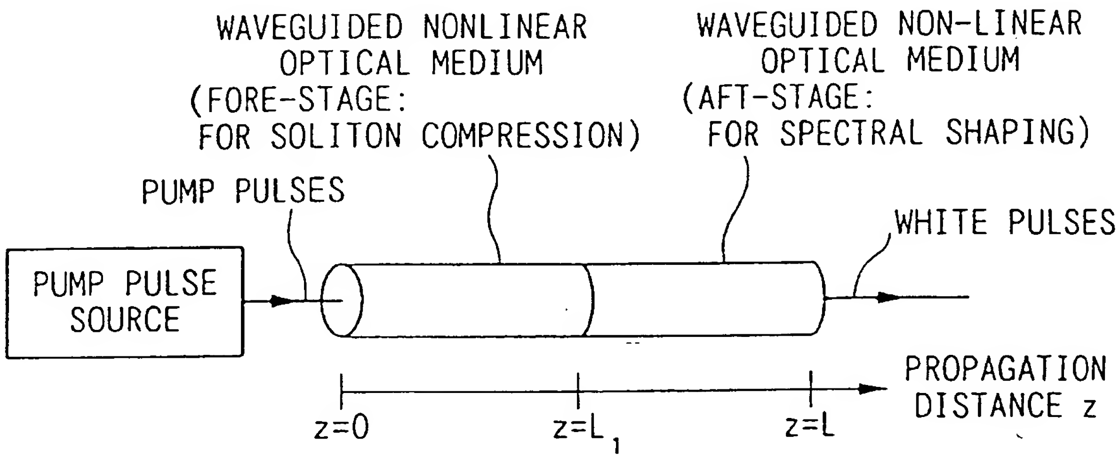

WAVEGUIDED NONLINEAR OPTICAL MEDIUM (FORE-STAGE: FOR SOLITON COMPRESSION)
WAVEGUIDED NON-LINEAR OPTICAL MEDIUM (AFT-STAGE: FOR SPECTRAL SHAPING)
PUMP PULSES
WHITE PULSES
PUMP PULSE SOURCE
PROPAGATION DISTANCE z
z=0
z=L1
z=L

FIG.17

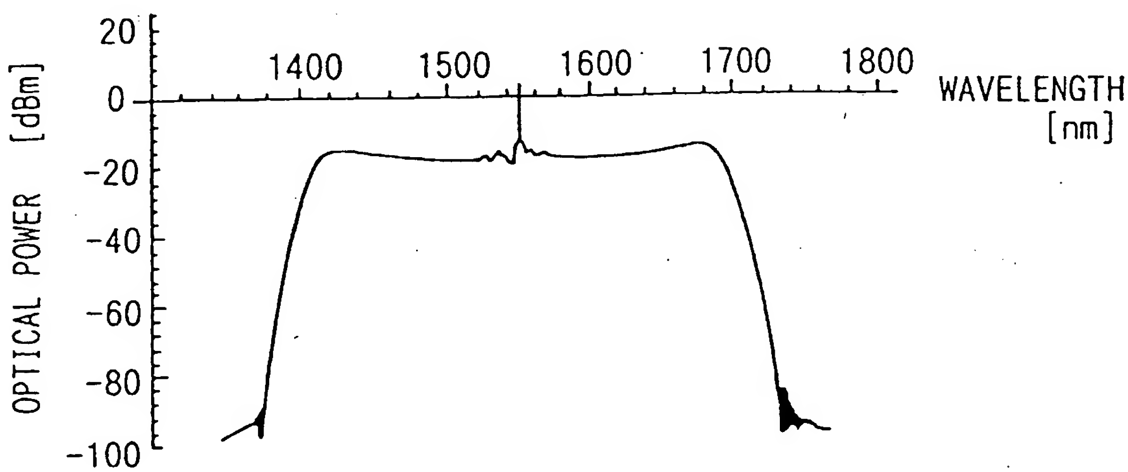

OPTICAL POWER [dBm]
20
0
-20
-40
-60
-80
-100
1400
1500
1600
1700
1800
WAVELENGTH [nm]

FIG.19

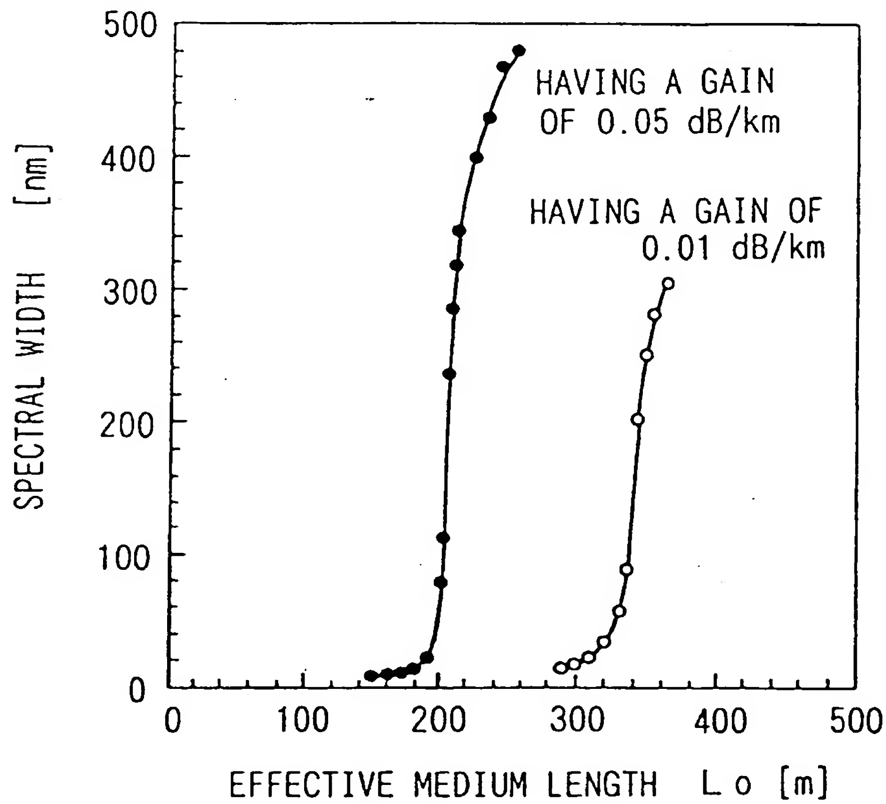

500
400
300
200
100
0
SPECTRAL WIDTH [nm]
HAVING A GAIN
OF 0.05 dB/km
HAVING A GAIN OF
0.01 dB/km
0
100
200
300
400
500
EFFECTIVE MEDIUM LENGTH Lo [m]

FIG.22

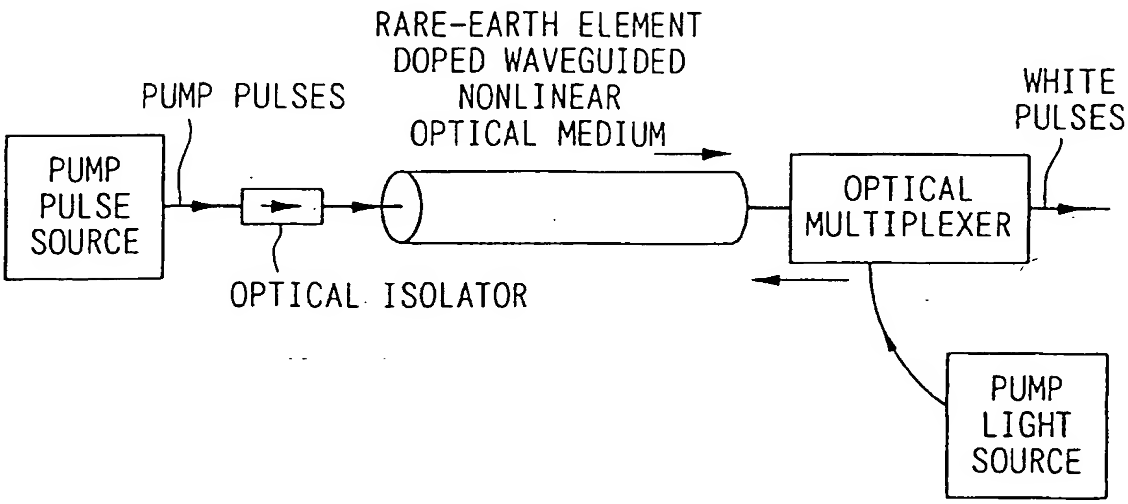

RARE-EARTH ELEMENT DOPED WAVEGUIDED NONLINEAR OPTICAL MEDIUM
PUMP PULSES
WHITE PULSES
PUMP PULSE SOURCE
OPTICAL MULTIPLEXER
OPTICAL ISOLATOR
PUMP LIGHT SOURCE

FIG.23

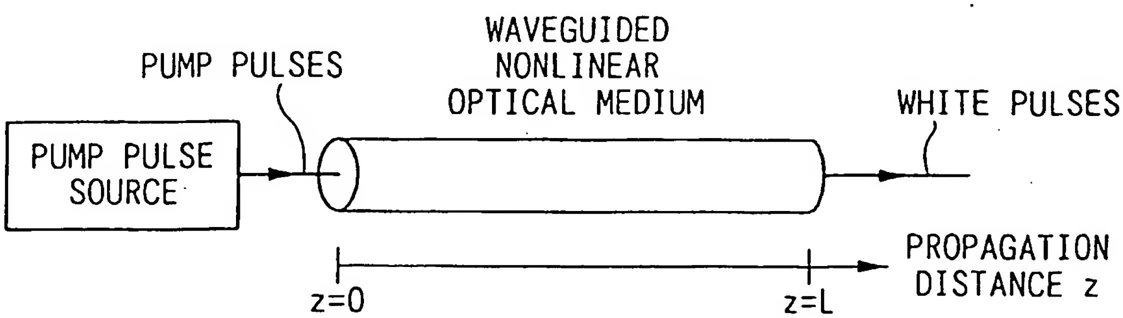

WAVEGUIDED NONLINEAR OPTICAL MEDIUM
PUMP PULSES
WHITE PULSES
PUMP PULSE SOURCE
PROPAGATION DISTANCE z
z=0
z=L

FIG.25

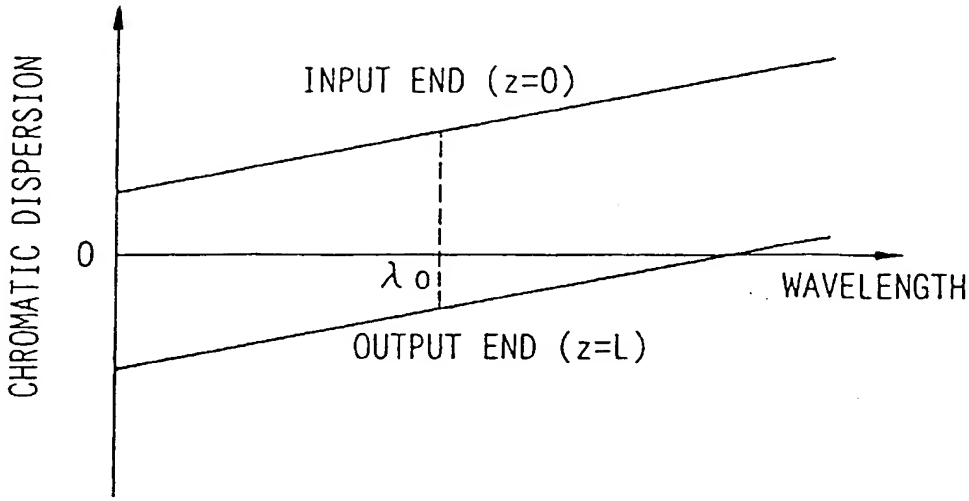

CHROMATIC DISPERSION
INPUT END (z=0)
0
λo
WAVELENGTH
OUTPUT END (z=L)

FIG.26

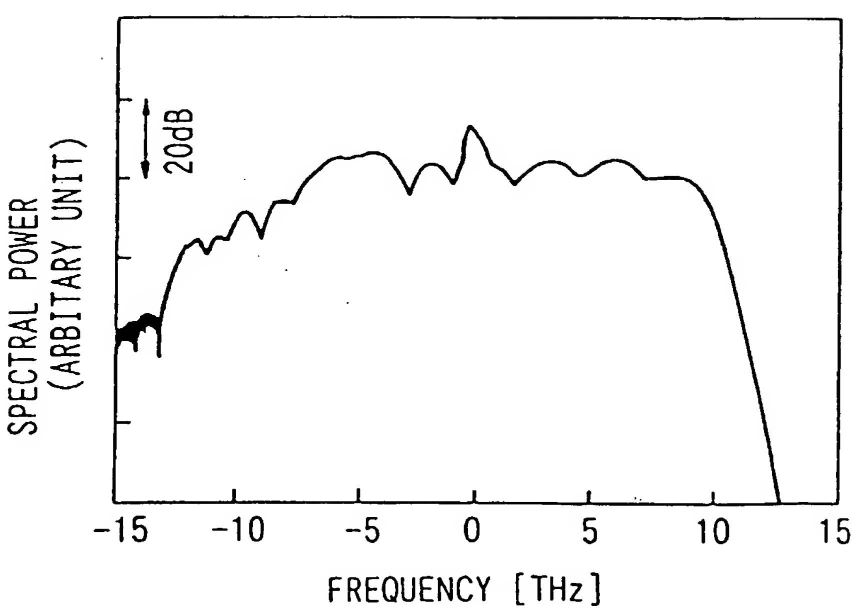

SPECTRAL POWER
(ARBITARY UNIT)
20dB
-15
-10
-5
0
5
10
15
FREQUENCY [THz]

FIG.29

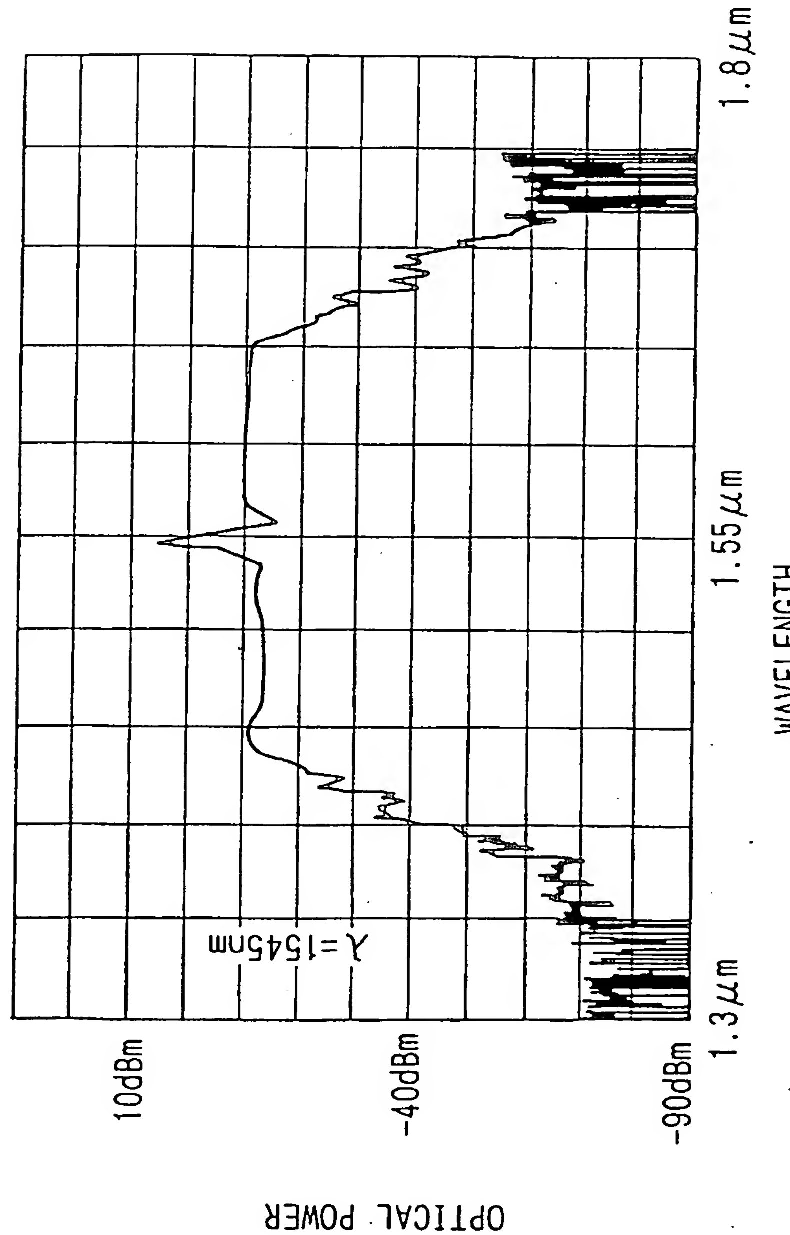

λ=1545nm
10dBm
-40dBm
-90dBm
OPTICAL POWER
1.3μm
1.55μm
1.8μm
WAVELENGTH

FIG.32

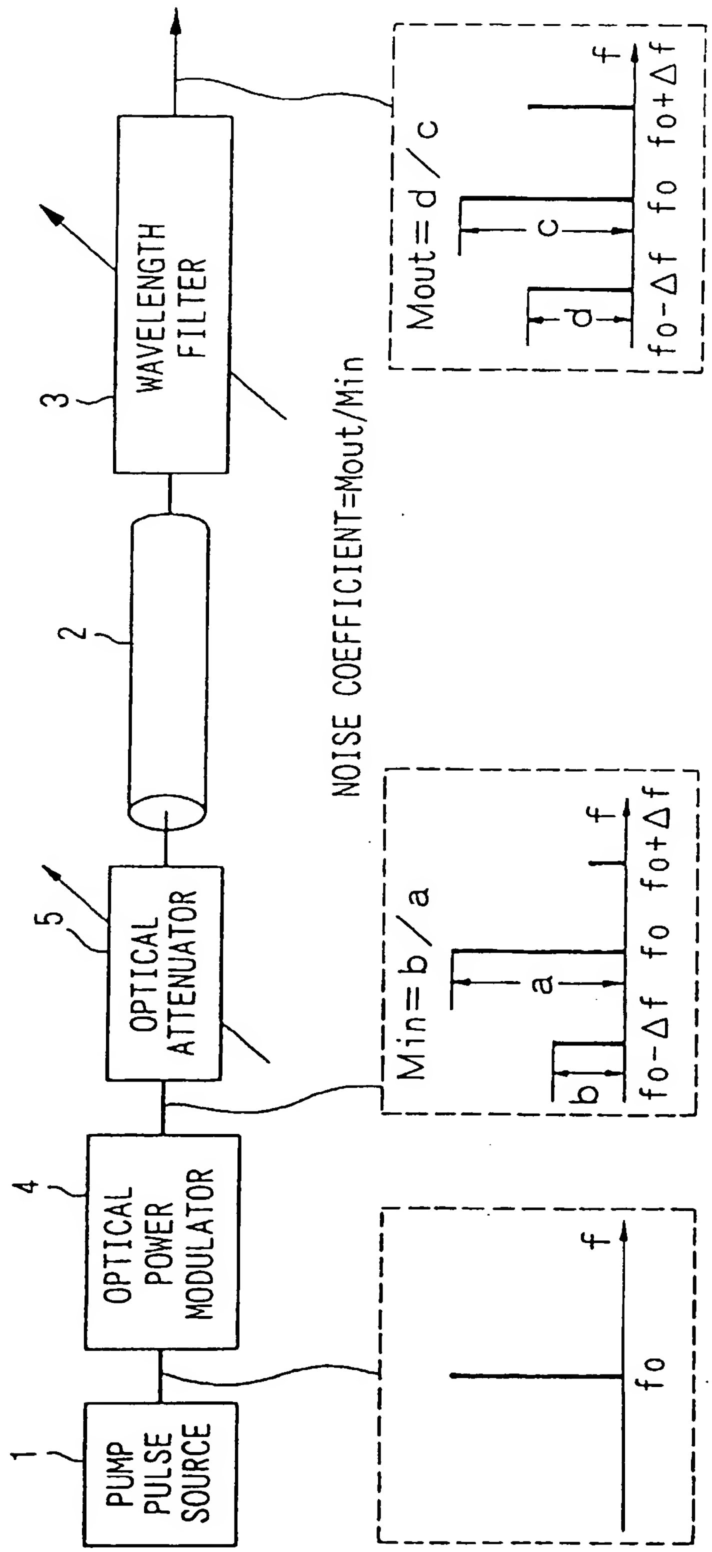

1
PUMP PULSE SOURCE
4
OPTICAL POWER MODULATOR
5
OPTICAL ATTENUATOR
2
3
WAVELENGTH FILTER
f
fo
Min=b/a
b
a
fo-Δf
fo
fo+Δf
f
NOISE COEFFICIENT=Mout/Min
Mout=d/c
d
c
fo-Δf
fo
fo+Δf
f

FIG.34A

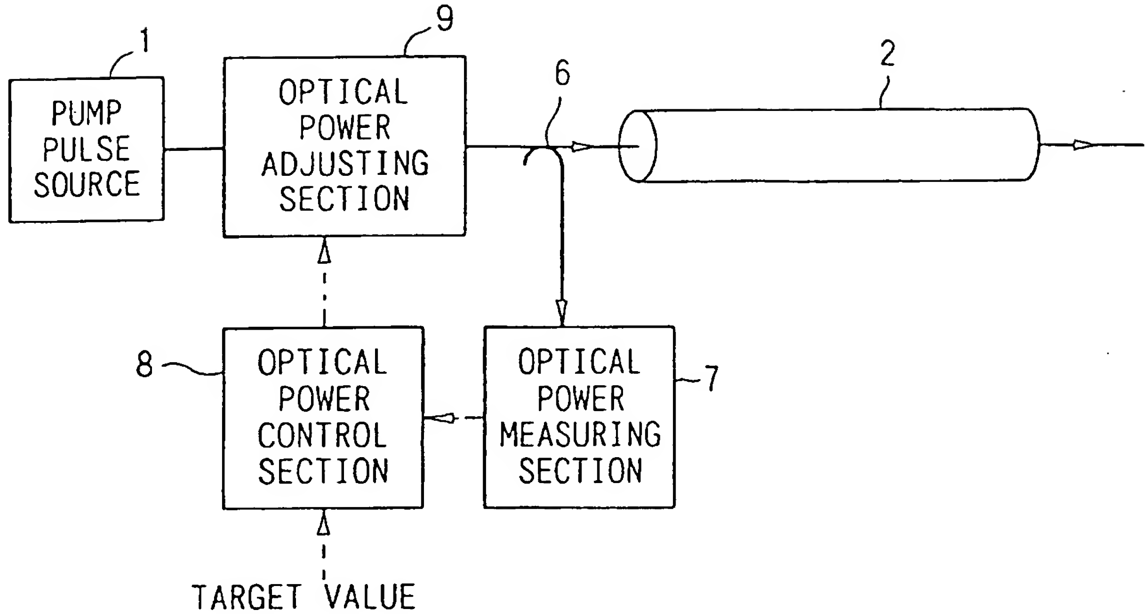


FIG.34B

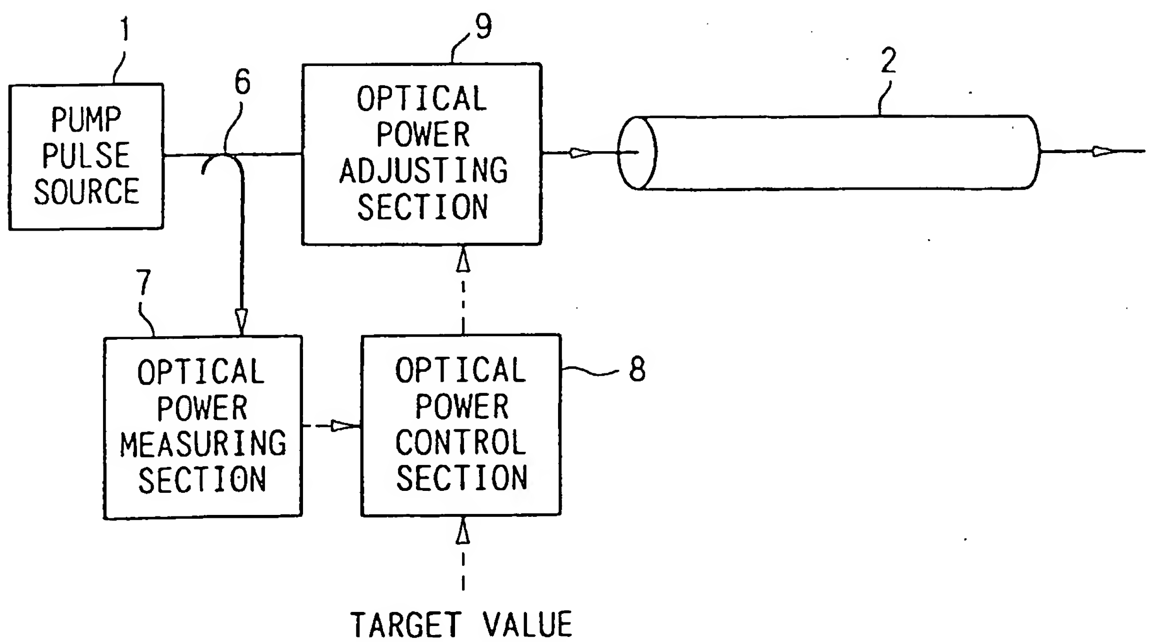


FIG.37

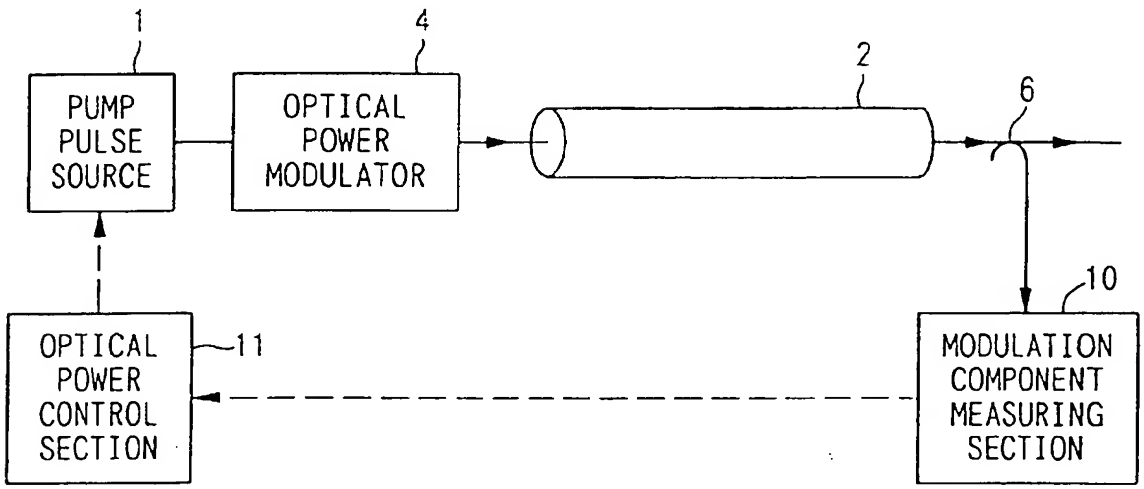

1
4
2
6
PUMP PULSE SOURCE
OPTICAL POWER MODULATOR
10
OPTICAL POWER CONTROL SECTION
11
MODULATION COMPONENT MEASURING SECTION

FIG.38

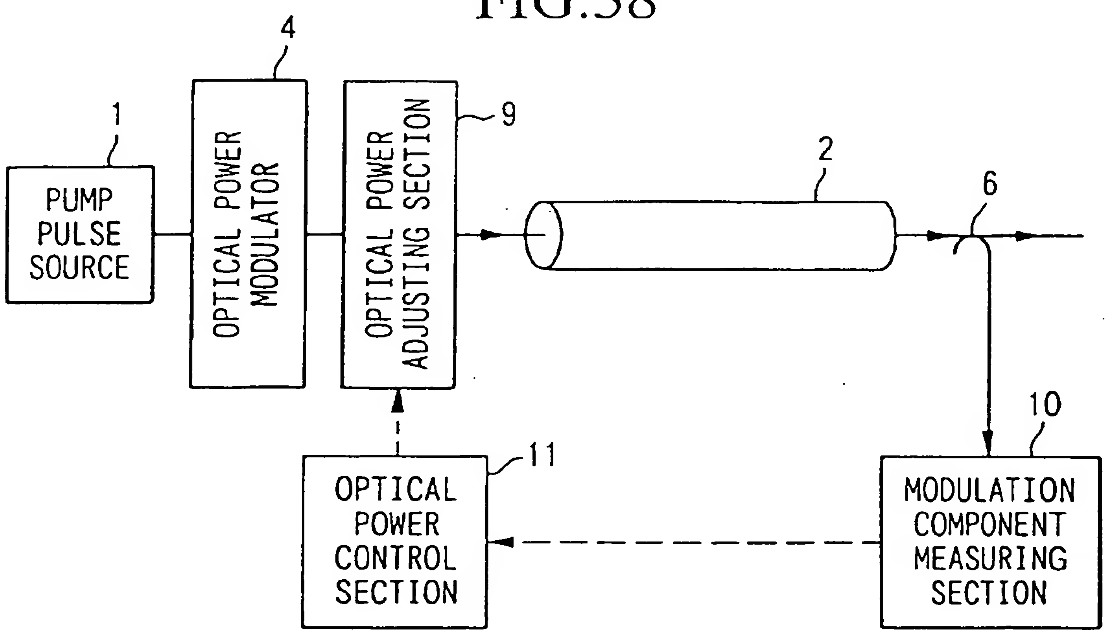

4
1
9
2
6
PUMP PULSE SOURCE
OPTICAL POWER MODULATOR
OPTICAL POWER ADJUSTING SECTION
10
11
OPTICAL POWER CONTROL SECTION
MODULATION COMPONENT MEASURING SECTION

FIG.41

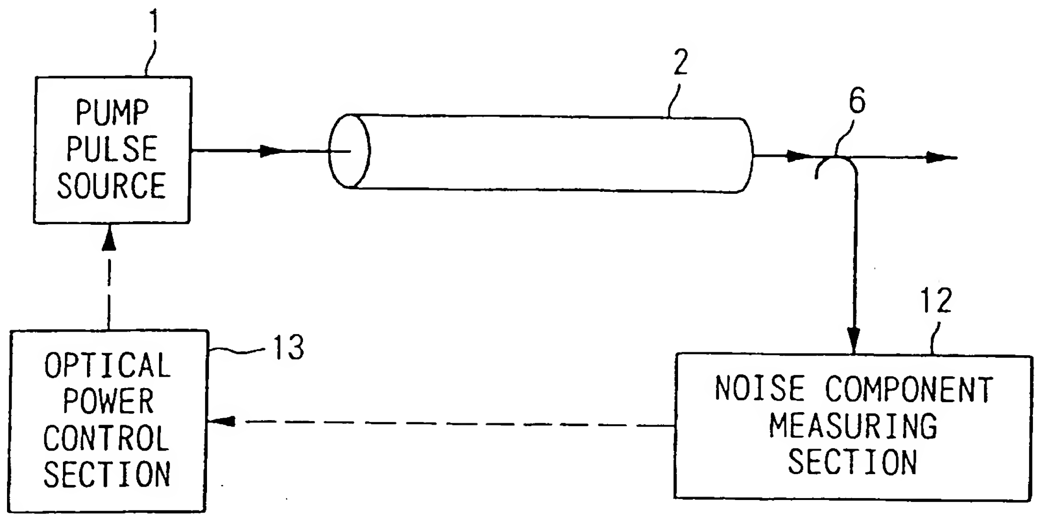

1
PUMP PULSE SOURCE
2
6
12
OPTICAL POWER CONTROL SECTION
13
NOISE COMPONENT MEASURING SECTION

FIG.42

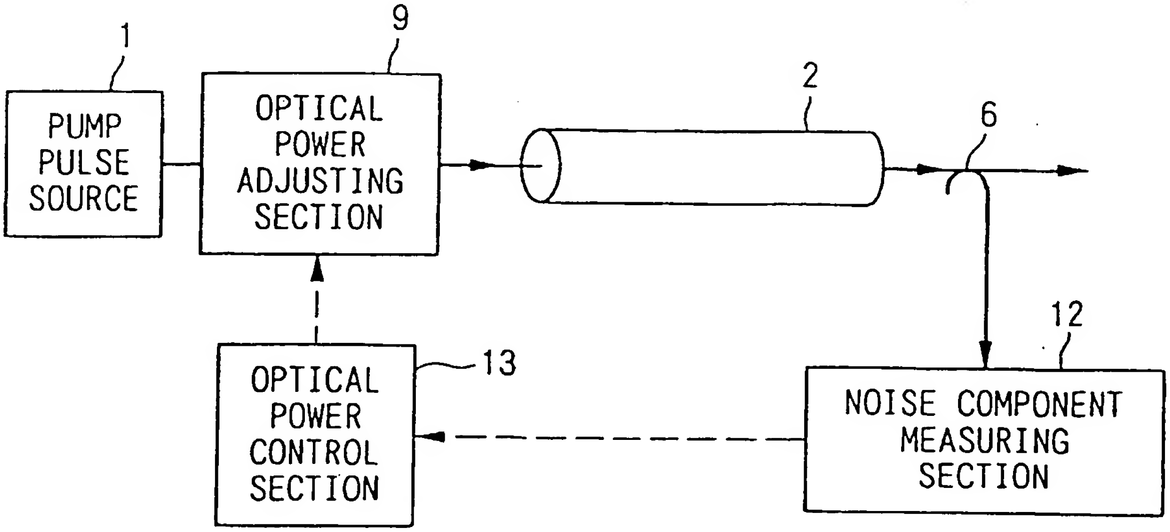

1
PUMP PULSE SOURCE
9
OPTICAL POWER ADJUSTING SECTION
2
6
12
OPTICAL POWER CONTROL SECTION
13
NOISE COMPONENT MEASURING SECTION

FIG.45

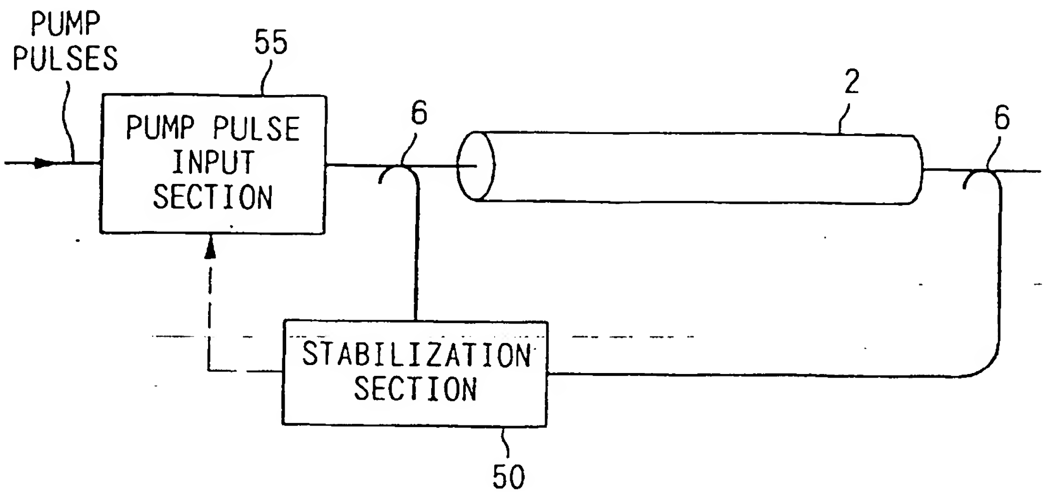

PUMP
PULSES
55
PUMP PULSE
INPUT
SECTION
6
2
6
STABILIZATION
SECTION
50

FIG.56

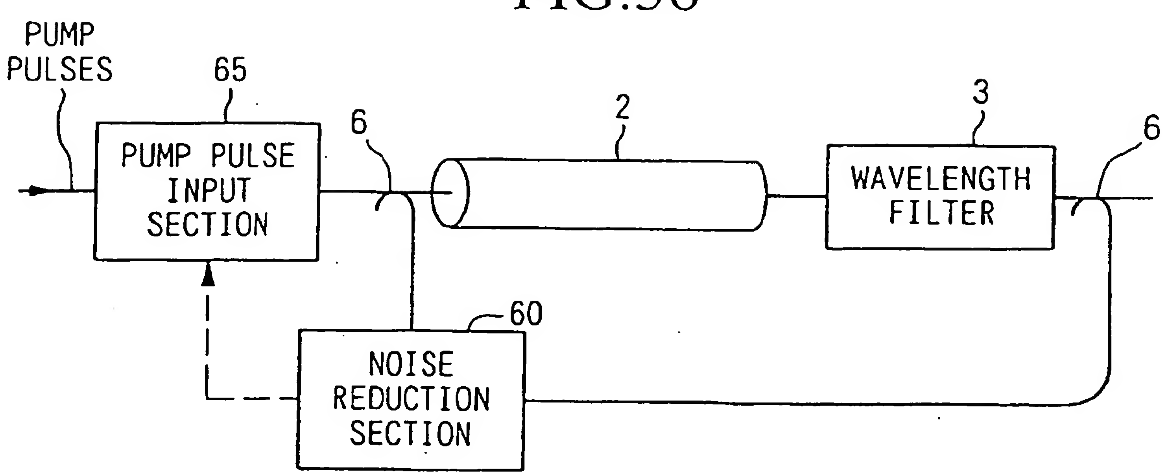

PUMP
PULSES
65
PUMP PULSE
INPUT
SECTION
6
2
3
WAVELENGTH
FILTER
6
60
NOISE
REDUCTION
SECTION

FIG.48

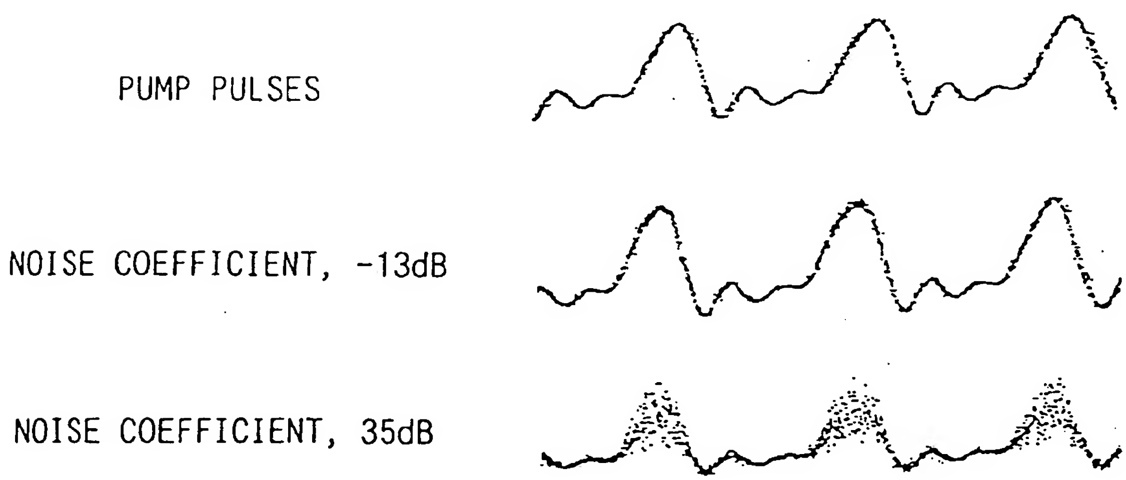

PUMP PULSES
NOISE COEFFICIENT, -13dB
NOISE COEFFICIENT, 35dB

FIG.50

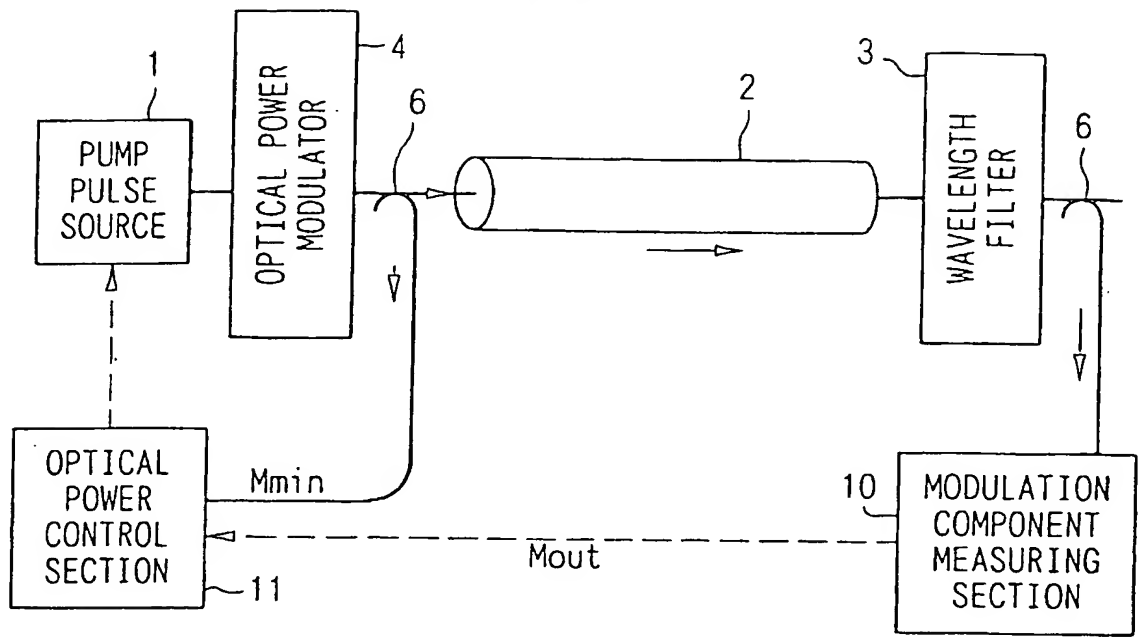

PUMP PULSE SOURCE
1
OPTICAL POWER MODULATOR
4
6
2
3
WAVELENGTH FILTER
6
OPTICAL POWER CONTROL SECTION
Mmin
10
MODULATION COMPONENT MEASURING SECTION
Mout
11

FIG.51

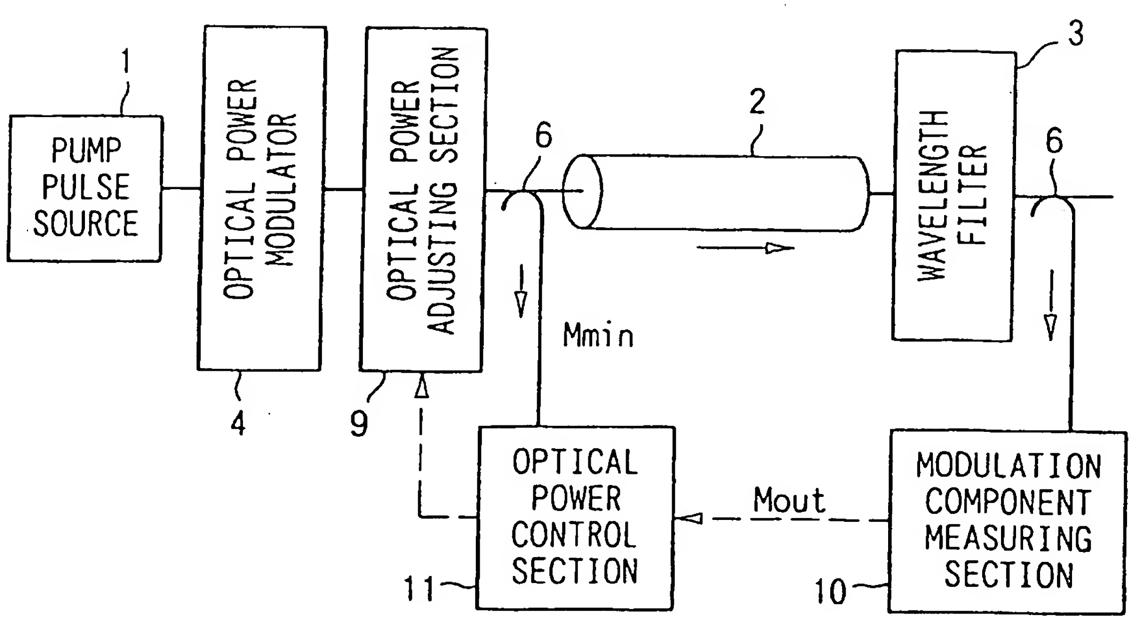

1
PUMP PULSE SOURCE
OPTICAL POWER MODULATOR
OPTICAL POWER ADJUSTING SECTION
6
2
3
WAVELENGTH FILTER
6
Mmin
4
9
OPTICAL POWER CONTROL SECTION
Mout
MODULATION COMPONENT MEASURING SECTION
11
10

FIG.54

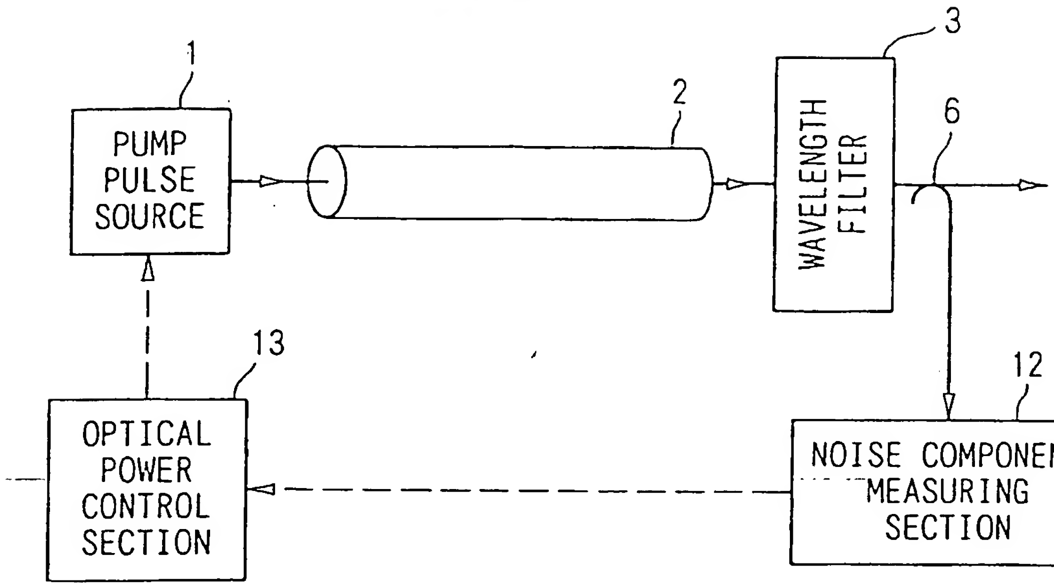
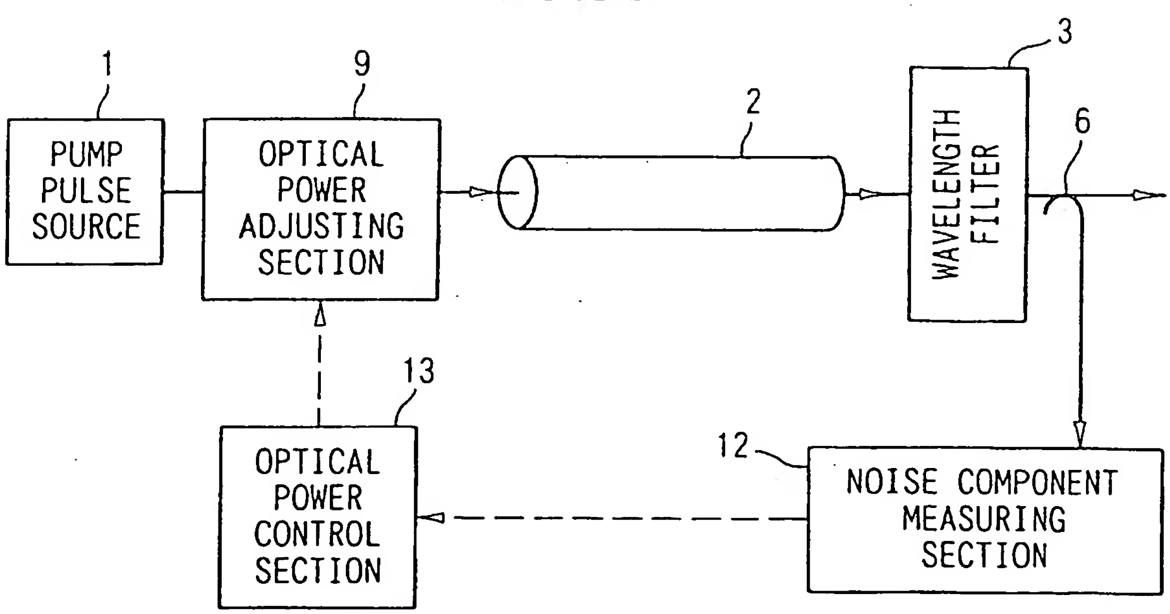

PUMP PULSE SOURCE
1
2
3
WAVELENGTH FILTER
6
13
OPTICAL POWER CONTROL SECTION
12
NOISE COMPONENT MEASURING SECTION

FIG.55


1
PUMP PULSE SOURCE
9
OPTICAL POWER ADJUSTING SECTION
2
3
WAVELENGTH FILTER
6
13
OPTICAL POWER CONTROL SECTION
12
NOISE COMPONENT MEASURING SECTION